Ship Design and Construction

Written by an International Group of Authorities

Thomas Lamb, Editor

Volume I

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A Word from the President

With this new edition of SHIP DESIGN AND CONSTRUCTION the Society of Naval Architects and Marine Engineers again advances the cycle of revision and updating of its major textbooks. The third edition of *Marine Engineering* was released in 1992, while the fourth edition of *Principles of Naval Architecture* is in the final stages of preparation. Over the decades since the first editions of these three books were published they have not only served their intended and primary purposes of educating generations of students and providing reference material for practicing professionals, but have often provided international members of the marine community with their first introduction to the Society. This new edition acknowledges the international applicability of its content and the growing international influence of the Society in the geographical diversity of its authors.

While the content of this edition is entirely new and up to date, the philosophy of preceding editions is retained: the book again addresses the practical aspects of ship design and shipbuilding that are relevant to shipowners and operators as well as to the designers and builders. Expanding the book to two volumes with 55 chapters has permitted an enormous increase in the breadth and depth of content. Professor Thomas Lamb's diligence and persistence as Editor have rewarded the Society and the profession with a book that is virtually a whole professional library in two volumes.

As an active and involved member of the Society I am well aware of the level of effort that goes into the preparation and publication of such a significant treatise as SHIP DESIGN AND CONSTRUCTION, and as President I am pleased and honored to use this space to thank Professor Lamb and all of those who worked with him, including the Chairman and members of the Control Committee, the authors, the reviewers, and all of the other contributors. Without their efforts this major and, I believe, necessary and successful book would not have been possible. This new edition of SHIP DESIGN AND CONSTRUCTION will stand as a credit to the Society, an inspiration to its readers, and a benefit to the industry for many years to come.

Bruce S. Rosenblatt
President

Foreword

With the passage of time since the 1980 edition of *Ship Design and Construction,* progress in the related arts and sciences has increasingly dictated the need for an updated version. Accordingly, in January 1996, SNAME's Executive Committee directed that the revision proceed promptly and approved the formation of the Control Committee. In February 1996, the editor, Professor Thomas Lamb, was appointed.

SNAME embarked on a program of publishing significant treatises on the subject of naval architecture, marine engineering, and shipbuilding with the 1939 edition of *Principles of Naval Architecture.* This was followed in 1942 with the publication of *Marine Engineering* and in 1955 with *Design and Construction of Steel Merchant Ships.* This present edition of *Ship Design and Construction* evolved from the 1955 *Design and Construction of Steel Merchant Ships* and the 1969 and 1980 revisions that bore the same title as the current edition. The organization of the subject matter of this new edition, however, is totally different from what was contained in the 1980 edition; in fact it is a complete re-write. There is a change not only in the text material but also in the philosophy in which the material is presented.

The 1980 edition concerned itself with the practical aspects of ship design as they relate to the requirements of the owner and operator and as they relate to the characteristics of the mission that the ship is to perform. Producibility of the ship was stressed as a design goal as well as the need to investigate shipbuilding and ship operating economics to derive a cost-effective vessel that would perform the intended task. In addition to the design aspects, coverage was provided of such subjects as shipbuilding contracts, government regulations, shipyard production techniques, launchings, trials, and guarantee surveys. The current edition updates and expands on this material and incorporates a complete change in presentation. The book has been organized in two volumes for the first time. The first comprises the technical aspects of the design and construction and the second provides details on the application to specific ship types.

The purpose of the book remains essentially the same as that of the prior editions-namely, a textbook "to assist students and others entering the field of shipbuilding towards a knowledge of how merchant ships are designed and constructed and to provide them with a good background for further study." Nevertheless, a number of considerations led the Control Committee to modify extensively the scope and organization of the book. The increasing globalization of shipbuilding and the development of commercial ship design outside the U.S. dictated that the new book have international authorship. That this was accomplished can be seen by the fact that the authors are from 14 countries.

The Committee reviewed the 1980 edition of the book and determined it:

- did not provide individual chapters on specific ship types,
- in some cases, such as with launching, there appeared to be an imbalance in the level of detail in which a subject was intended,
- certain technical areas could be blended into coverage of specific ship types such as Chapters 10 and lion dry cargo handling and transportation of liquid cargo, respectively, .

- authorship was mainly from U.S.,
- naval vessels were not specifically considered, and
- there was a clear absence of a significant presentation on the impact of machinery.

As a result, the Committee concluded:

- develop the new edition in two volumes with the first containing a treatment of general technical subjects and the second treating specific ship types,
- naval vessels should be considered,
- in the chapters for specific vessel types address what is unusual relating to the general technical subject chapters in the first volume as applied to the design and production of these vessels,
- work towards incorporating a more worldwide representation of chapters' authorship as much of the technology exists overseas, and
- the essentially re-written book would as a result of its content not only address its primary intended mission but would be a significant source of reference material for the practitioner.

Through the cooperation of the Publications Committee and the Editors and Control Committees for this book and for the forthcoming edition of *Principles of Naval Architecture,* SNAME continues to provide a compatible series of volumes that will cover the gamut of technology from the basic concept of a vessel to the ultimate delivery to its owner and operator. This has proved to be an exacting task, particularly during a period when new intergovernmental regulations have been undergoing rapid development and when environmental demands have forced changes not only in the ships themselves but also in the facilities where they are constructed and the waterways in which they operate.

This current edition is most significantly the creation of the Editor, Professor Thomas Lamb, with the support of the authors. The Control Committee has been of assistance, but Professor Lamb has provided the focus and painstaking effort to see this complete re-write through. The task has been made much more difficult by the decreased external support of professional society activities. A work like this becomes a labor of devotion by the Editor. SNAME owes a debt of gratitude to Professor Lamb for this work.

As a result of the collaborative effort involved in its preparation, the 2003 edition of *Ship Design and Construction* will better meet the current needs of all those involved in ship design/production. Because of its comprehensive treatment and the near impossibility for one person to retain specialized knowledge in every technical field covered by this edition, the book should be valued by practicing ship designers and builders as well.

Dr. John C. Daidola, P.E.
Chairman, Control Committee

Preface

This book has a great heritage, namely, the earlier editions in 1955, 1969 and 1980. However, the needs for a new edition derive not just from the time that has past since the last edition, but because of the exciting and challenging situation that ship designers and shipbuilders, not only in the U.S. but around the world, face today. The demand for ships has never been greater and the associated commercial as well as technical challenges are worthy of any vibrant industry. However, there are many problems.

Shipbuilding is a global industry and one that can be introduced relatively easily into developing countries. Because of this and even more important, because it uses significant numbers of workers, it is often used by developing nations as a way to develop an employment and industrial base as well as to attain a foundation for balance of payments exports to pay for the technology imports they need to develop.

Even with the higher demand for ships the world shipbuilding capacity is still greater by more than 50%, with new shipyards still being built. This results in fierce competition and, unfortunately, low world shipbuilding prices. The ship prices are set by the lowest cost shipbuilders, often in developing countries, where financial support is given to the industry to attain national goals. This can upset the normal competitive forces and result in some traditional shipbuilding countries having problems in meeting the low prices and even having to exit shipbuilding, as was the case of Sweden and Britain in the 1980s.

The situation in the U.S. is somewhat different in that it has not been a player in the international commercial shipbuilding market since the 1950s. Also, as the U.S. shipbuilding industry operates in a protected environment, and as long as it keeps out of the international market, it is not directly affected by world pricing. However, today the U.S. shipyards are facing a dilemma. With U.S. Navy new ship orders decreasing well below the level to keep the U.S. shipyards fully occupied, they must find other markets or face closure. In the past the Jones Act provided a demand for commercial ships and at the time of writing there are tankers, RO/ROs, cruise ships and a container ship being constructed in U.S. shipyards. This is a welcome development and one that should continue for some time as the existing Jones Act ships are becoming quite old and in need of replacement.

This in turn creates a demand for educated and experienced ship designers and shipbuilders not only in the U.S. but in the developing countries, for obvious reasons, and also in the traditional shipbuilding countries where demand is falling, as the existing knowledge and skills are lost due to industry scale-down.

All the above creates the need for this book, as it captures existing knowledge from around the world on best ship design and construction practices, provides a readily accessible record of this knowledge, and thus provides a way for students, as well as inexperienced ship designers and shipbuilders, to acquire the knowledge they need in their learning and work.

Many outsiders do not perceive shipbuilding as a "high-tech" industry. However, it does use specific high technology in its processes to design and construct ships and other marine equipment, which can be among the most complex products in the w6rld.

It also does not change as quickly as some other industries. That this is so is demonstrated by the fact that the previous edition of this book is still a useful and relevant reference book for students and practitioners of ship design and construction. Also, when talking of shipyards, the one U.S. yard and most of the Japanese shipyards, built in the 1960s, are still considered the *new* shipyards.

Nevertheless, much has changed since the publication of the last printing of the 1980 edition of the book, and it is time for a revision. Actually this edition is not just a revision but a complete re-write and significant format change. Another change is in its authorship. Shipbuilding is a global industry and the U.S. is not currently a leader in commercial ship construction. It was therefore appropriate to seek the best authors from the shipbuilding world, not just from the U.S., especially as the U.S. has not been involved recently in some areas of the commercial ship design covered.

It is being published in two volumes for the first time. Volume I contains the generic ship design theory and construction information without application to specific ship types, except where it is necessary to completely describe the application. Volume II contains chapters on specific ship types and the special design issues applying thereto. The Book Control Committee decided the contents.

An obvious change is the impact of computers and information technology on the design and construction of ships and marine vehicles. There has also been a number of new ship and offshore platform design types that have appeared since the publication of the previous book.

It is the intent of this edition of *Ship Design and Construction* to cover the changes and provide an instruction and information book that will be useful well into the 21st century. There is so much information to cover that the problem facing the Book Control Committee was not what to include but what to leave out. Rather than repeat information that is readily available to U.S. readers, it references other state-of-the-art publications from groups such as SNAME, the National Shipbuilding Research Program, and the USA Shipbuilding web site.

Specific changes are that the new book does not include chapters on Load Line, Tonnage, and Launching that were new in the 1980 edition. Nor does it include individual chapters on Cargo Handling-Dry Cargo, Transport of Liquid and Hazardous Cargoes, and Trials and Preparation for Delivery-topics that are covered in other chapters. It was also decided not to include a glossary, as there are many others already published and even some available on the Internet.

The new book focuses on the fact that there are many ship types and within each type many variations. Therefore, each major ship type is covered in a separate chapter in Volume II. In addition, a chapter on Offshore Production and Drilling is included. For the first time chapters on Naval Surface Vessels and Submarines are included. This allowed the aspects of ship design and construction that are generic to be placed in Volume I.

New topic chapters have been added in Volume I, such as the Marine Environment. It has always been a puzzle to the editor how ship designers could design products to operate in the oceans of the world without any knowledge of the oceans. So this chapter gives an introduction to this important subject. Others are The Marine Industry, The Ship Acquisition Process, Mass Properties, Simulation-Based Design, Computer-Based Tools, Design/Production Integration, Human Factors in Ship Design, Reliability-Based Structural Design, and Machinery Considerations.

The symbols used throughout the book are in accordance with the international standard. Units of measure are all metric and the past practice of displaying corresponding U.S. customary *English* units in parentheses is not used.

Thomas Lamb, *Editor*

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John Boylston
Dr. Charles Cushing
Peter Gale
Robert Geary
Ronald Kiss
George Knight
Capt. Jeffrey Lantz
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Thomas Lamb, *Editor*

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Author Biographies for Volume /

Chapters 1, 14, 20, 22 and 26

Thomas Lamb is a Research Scientist, Director of the Shipbuilding Research Lab and the NAVSEA Ship Production Science Program, and an adjunct professor in the Department of Naval Architecture and Marine Engineering at the University of Michigan. He served a 5-year apprenticeship as a Shipwright in HM Dockyard, Rosyth, Scotland, from 1950-1955. He received his Honors B.S. from Kings College, Durham University in 1958 and an MBA from Tulane University in 1990. He is a Fellow of the Society of Naval Architects and Marine Engineers, the Royal Institution of Naval Architects and the Institute of Marine Engineering Science and Technology, and a Member of the American Society of Naval Engineers, the Society of Logistic Engineers and the International Council on Systems Engineering. He is a Registered Professional Engineer in Washington and Wisconsin, a British Chartered Engineer and a European Engineer.

Chapter 2

Dr. Guy A. Meadows is a Professor of Applied Ocean Physics and Director of the Ocean Engineering and Marine Hydrodynamics Laboratories in the Department of Naval Architecture and Marine Engineering at the University of Michigan. He received his B.S.E (1972) and M.S.E. (1974) in Mechanical Engineering from Michigan State University, and his Ph.D. in Marine Science from Purdue University in 1977. He joined the faculty ofthe University of Michigan in 1977, where he established his research programs in field and analytical studies of marine environmental hydrodynamics, active microwave remote sensing of ocean dynamics and the development of *in situ* and remote oceanographic instrumentation and data acquisition systems designed to measure the spatial and temporal structure of coastal boundary layer flows.

Dr. Lorelle A. Meadows is a Research Scientist in Engineering in the Department of Naval Architecture and Marine Engineering at the University of Michigan. She received her B.S. (1983) in Marine Geochemistry, M.S. (1985) in Physical Oceanography and her Ph.D. (2002) in Oceanic Science from the University of Michigan. She joined the staff of the University of Michigan in 1986 where she worked to develop research programs in environmental nearshore dynamics and remote sensing of ocean surface processes. In addition to overseeing an active research program, she teaches upper-level ocean dynamics and introductory engineering courses.

Chapter 3

Tim Colton is President of Maritime Business Strategies, LLC, a consulting firm specializing in improving the performance of businesses and organizations in the maritime industry. He started his career in shipbuilding in 1958 at Lithgows Limited, Scotland, where he served an apprenticeship and became Planning Manager. After a stint as Production Manager of a Canadian shipyard, he joined John J. McMullen Associates in New York City in 1968, where he worked primarily ,as a consultant to the shipbuilding industry. He returned to active shipbuilding in 1978, as VP, Planning, for Levingston Shipbuilding, Orange, Texas, but moved back north in 1982 when Levingston bought Sun Ship, to be VP, Marketing, for Pennsylvania Shipbuilding. In 1988, he became a shipbuilding consultant again, this time with his own firm, Colton & Company, in Washington DC. He returned to shipbuilding a second time in 1998, joining Halter Marine Group as Senior VP, Production Support, subsequently becoming Senior VP, Business Development, for Friede Goldman Halter. He left FGH in May 2001 to return to consulting. He has a B.Sc. in naval architecture from the University of Glasgow and an M.S. in industrial engineering from Columbia University. He is the Chairman of the Public Policy Committee of the Society of Naval Architects and Marine Engineers, and also serves on the U.S. Advisory Committee of Lloyd's Register.

Chapter 4

Dr. Charles Cushing has been President of C. R. Cushing & Co., Inc. since its founding in 1968. His firm of naval architects and marine engineers has been responsible for the design and/or construction of over 250 ships worldwide, including container ships, tankers, bulk carriers, ITB's, passenger vessels and other types. Dr. Cushing is recognized as one of the "container pioneers," having started with Pan Atlantic (later renamed Sea Land) and served as their Chief Naval Architect. He served at sea on a Danish ship as a seaman, and later on U.S. passenger and cargo ships as a cadet and licensed deck officer. He is a graduate of the U.S. Merchant Marine Academy, SUNY Maritime, MIT and Cardiff College. He has lectured at World Maritime University since 1986, and lectures regularly at other institutions. He is a licensed Professional Engineer, Charter Engineer (UK) and Euro Engineer.

Chapter 5

Mr. Gale has over 42 years of marine experience, including an extensive background in planning, performing, integrating, managing and reviewing naval ship designs. He spent nearly 29 years as a naval architect employed by the Naval Sea Systems Command and its predecessor organizations. After leaving NAVSEA in 1988, Mr. Gale taught naval architecture and ship design courses at Webb Institute for three years. In 1991, Mr. Gale joined John J. McMullen Associates, Inc. as Chief Naval Architect of the Naval Ship Design and Engineering Operation. In this position, he manages projects requiring his ship design management and integration expertise and also provides ship design consulting services both within the company and to outside clients. Mr. Gale served as a consultant to Bath Iron Works Corp. during their Arsenal Ship design effort and supported the CVX Project Office at NAVSEA. Recently, he has been supporting Ingalls Shipbuilding on the DD21, now DD(X), Gold Team. He was awarded a Bachelor of Science in Naval Architecture and Marine Engineering from the Webb Institute of Naval Architecture in 1959, and a Master of Science in Nautical Engineering from the Stevens Institute of Technology in 1964. Mr. Gale is a life member of SNAME and RINA. He is a member of ASNE and the Naval Research Advisory Council.

Chapter 6

Harry Benford has been professionally associated with the University of Michigan's Department of Naval Architecture and Marine Engineering since 1948, and gained Emeritus status in 1982. He is best known for his pioneering work in applying economics to decision making in ship design. He has published extensively in matters pertaining to his chosen field and is the recipient of several SNAME awards, including the Taylor medal.

Chapter 7

Mark R. Buetzow is Manager of Upstream Projects for ChevronTexaco Shipping Company LLC. He holds a B.S. degree in mechanical engineering and an M.S. degree in naval architecture from the University of California, Berkeley. He is a licensed Professional Engineer in the state of California. Mr. Buetzow has held various engineering and operations positions in ChevronTexaco Shipping over the last 27 years. Besides other engineering and operations related work, he has provided design and/or project management services for numerous tankers, FPSOs, tu~s, and barges. He is currently a member of the ABS Americas Divisional Technical Committee, the Tanker Structure Cooperative Forum, and the Society of Naval Architects and Marine Engineers.

Dr. Philip C. Koenig is Associate Director for Industrial Economics and Technology at the Office of Naval Research, International Field Office (Asia) in Tokyo, Japan. A graduate of Webb Institute of Naval Architecture, he received an M.S. degree in naval architecture from the University of California, Berkeley, an Sc.D. degree in engineering economics from George Washington University, and is a licensed Professional Engineer in the state of California. Dr. Koenig was previously a design and construction engineer at Chevron Shipping Company in San Francisco, California and a naval architect at Davi<;lTaylor Model Basin, Carderock, Maryland. He serves on SNAME's Journal of Ship Production Committee and Marine Technology Committee.

Chapter 8

Jeff Lantz has recently retired from the USCG where he was the Chief of the Coast Guard's Office of Design and Engineering Standards and is responsible for the safety standards for vessel designs in the areas of structure, stability, electrical, mechanical, control, firefighting and lifesaving. He is also responsible for the Prevention Through People (PIP) and risk-based decision-making programs for the Coast Guard's marine safety, security and environmental protection programs. He also serves as the head of the U.S. delegation to IMO's Ship Design and Engineering sub-committee. He graduated from the Coast Guard Academy in 1974 and the University of Michigan in 1978, where he obtained advanced degrees in Naval Architecture and Marine Engineering and in Mechanical Engineering.

Glenn Ashe is presently assigned as Director of Government Operations for the American Bureau of Shipping and heads their Government Operations Office in Alexandria, Virginia. Mr. Ashe is a 1969 graduate of Georgia Tech with a degree in electrical engineering. After graduation he completed four years of active duty with the US Navy. Upon leaving active duty, he affiliated with the Naval Reserve and retired in 1994 having attained the rank of Captain. Upon leaving active duty, Mr. Ashe attended graduate school at MIT and graduated in 1975 with advanced degrees in Naval Architecture and Marine Engineering and Ocean Engineering. His professional career has included positions with the US Navy, US Coast Guard, Military Sealift Command and private naval architectural design firms. He joined the American Bureau of Shipping in 1990 as Director of Engineering for ABS Americas and was Director of Business Development in 1993 and assumed his present position as Director of Government Operations in October of 1995. Mr. Ashe is a member of ASNE and SNAME.

Chapter 9

Dr. Kenneth W. Fisher has been president of Fisher Maritime Transportation Counselors, Inc. since 1976. Dr. Fisher continues assisting numerous shipyards, shipowners, naval architects and vendors from many nations understand and avoid the potential pitfalls between the technical and project issues of ship construction, conversion, repair and design on one hand, and the legal and contractual issues on the other. Having received training as an arbitrator, he regularly acts as expert witness or arbitrator for resolving contract disputes in the marine industries. He is widely known for his seminars on the management of contracts for ship construction, repair, conversion and design, which have been attended by thousands of individuals from organizations in many nations. A graduate of Webb Institute of Naval Architecture, he has postgraduate degrees from the University of Michigan and the University of Sydney. Previously he was on the faculties ofthe State University of New York Maritime College, the University of Sydney and the University of New South Wales. Dr. Fisher is a Fellow of the Royal Institution of Naval Architects and a Life Member of SNAME.

Chapter 10

Laurent Deschamps is President of SPAR Associates, Inc., where he has over 25 years of work experience developing and implementing computerized shipyard planning and management control systems. Since the early 1980's, he has been involved in the development of automated cost estimating systems. In the 1990s these systems were linked to a variety of CAD and naval engineering software to expedite *Cost* evaluations of engineering trade-off studies. SPAR has been a prime contractor to the U.S. Navy's Product Oriented Design & Construction ("PODAC") Cost Model that provides features for estimating costs by interim product, manufacturing process and stage of construction. He earned his Bachelor of Science degree from Trinity College, Hartford, Connecticut and his B.S. in Mechanical Engineering from that same institution. He is a member of SNAME.

Chapter 11

Dr. Michael G. Parsons is a Professor of Naval Architecture and Marine Engineering at the University of Michigan where he has been teaching marine design for the past 18 years. Previous teaching was focused primarily in marine engineering. He served as Chair of that department from 1981-1991 and as Associate Dean of Undergraduate Education for the College of Engineering from 1991-1996. He received a B.S.E. (Naval Architecture and Marine Engineering) from the University of Michigan in 1963; a Certificate in Reactor Engineering from the Bettis Reactor Engineering School in 1965; a M.M.E. (Mechanical Engineering) from The Catholic University of American in 1969; and a Ph.D. (Applied Mechanics) from Stanford University in 1972. He served six years in the U.S. Navy assigned to BuShips/NAVSEA Code 08 and the Atomic Energy Commission Code 1500 prior to pursuing his Ph.D. He joined the faculty at Michigan in 1972. He is a Fellow of the Society of Naval Architects and Marine Engineers and is a member of the American Society of Naval Engineers, the American Society for Engineering Education, the U.S. Naval Institute, and the International Association of Great Lakes Research.

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Chapter 12

William Boze is currently the Manager of Naval Architecture at Northrop Grumman Newport News. He received both his Bachelors of Engineering degree in Naval Architecture from State University of New York Maritime College and his Third Assistant Engineer Coast Guard License for Steam & Motor Vessels Unlimited Horsepower in 1980. In his 22 years at Newport News he has participated in various stages of ship design and construction for a variety of ships. He also served six years in the United States Naval Reserve mostly in the capacity of Assistant Repair Officer at the Philadelphia Naval Base SIMA. He is a member of the Society of Naval Architecture and its Ship Design Technical Committee as well as the Society of Allied Weight Engineers.

Chapter 13

Jonathan Ross is the Director of Engineering at Proteus Engineering Division of Anteon Corporation. He received his BS in Mechanical Engineering from Carnegie-Mellon University and his MSE in Naval Architecture from the University of Michigan. As an Officer Candidate School Distinguished Naval Graduate, he received a commission in the U.S. Navy as an Engineering Duty officer. He is a registered Professional Engineer in Michigan and Maryland and a Chartered Engineer in Britain. Prior to joining Proteus Engineering he worked for Ross-McNatt, Inc, Gianotti and Associates, Inc., NOA, and the Johns Hopkins University Applied Physics Laboratory. His current specialties include CAD/CAE/CAM/CIM, computer aided ship design, and shipyard modernization. He was instrumental in introducing FORAN into North America. He is a member of SNAME and RINA.

Chapter 14

Thomas Lamb, see Chapter 1

Chapter 15

LT Scott Calhoun graduated from the U.S. Coast Guard Academy in 1995 with a Bachelor's Degree in Naval Architecture and Marine Engineering. After serving two years as a Student Engineer aboard U.S. Coast Guard Cutter *Dauntless* (WMEC-624), he attended the University of Michigan where in 1999 he was awarded a Master's Degree in Naval Architecture and Marine Engineering. He is currently assigned to the Human Element and Ship Design Division of U.S. Coast Guard Headquarters in Washington D.C., working on Crew Endurance Management research with the USCG Research and Development Center.

LT Sam Stevens graduated from the U.S. Coast Guard Academy in 1995 with a Bachelor's Degree in Mechanical Engineering. He served two years aboard U.S. Coast Guard Cutter *Mallow* (WLB-396) as a Deck Watch Officer, followed by two years at the National Drug Intelligence Center as an intelligence analyst. From 1999-2001, he attended the University of Michigan where he was awarded a Master of Science Degree in Naval Architecture and Marine Engineering and a Master of Science Degree in Kinesiology. He is currently assigned to the Human Element and Ship Design Division of U.S. Coast Guard Headquarters in Washington, D.C., working on Crew Endurance Management research.

Chapter 16

Robert L. Markle is President of the Radio Technical Commission for Maritime Services (RTCM), a non-profit scientific and educational organization, focusing on all aspects of maritime radio communications, radio navigation, and related technologies. Prior to that, he spent 27 years working at U.S. Coast Guard Headquarters in Washington, DC, in various assignments related to maritime safety. He concluded his Coast Guard career as Chief of the Lifesaving and Fire Safety Standards Division, where he administered U.S. programs on standards and enforcement for marine lifesaving, and fire protection systems.

Chapter 17

Bart Boon studied Naval Architecture at Delft University of Technology in The Netherlands from which he graduated in 1970 with ship structures as specialization. With a one-year scholarship from Lloyd's Register of Shipping he studied shipbuilding in various developing countries. In 1972 he joined IHC Gusto shipyard in Holland where he was involved in the structural and general design of several novel offshore units. These included several oil drilling jack-ups, dynamically positioned drillships, jack-ups for civil engineering purposes, and pipe-laying barges, among them the semi-submersible *Viking Piper*. After a reorganization of the Dutch shipbuilding industry and closure of the yard, Bart joined IHC Gusto Engineering in which the yard's design activities were continued. In 1986 he became professor of Mobile Offshore Structures Design at Delft University. After a few years' intermezzo at Twente University, where he headed the industrial liaison office, Bart rejoined Delft University in 1994 as Professor of Ship and Offshore structures. As such he also managed the Ship Structures Laboratory of the university. Since 2000 he has run his own company advising the ship and offshore industry on various structural subjects. He is member of the Standing Committee of ISSC, and the International Ship and Offshore Structures Congress.

Chapter 18

Dr. Philippe Rigo belongs to the National Fund for Scientific Research (NFSR) and works at ANAST, Department of Naval Architecture and Transport Systems of the University of Liege (ULg, Belgium). He has lectured on Analysis and Optimization Structures at Liege, Michigan and Hanoi Universities. He obtained his PhD Degree in 1988 from the University of Liege and the Highest Belgian Scientific Degree (Agrege de l'Enseignement Superieur Universitaire) in 1999. He received a postdoctoral fellowship from the JSPS at Kyoto University in 1990-91 and a Visitor Professor fellowship at Department of Naval Architecture and Marine Engineering of the University of Michigan. He worked for 7 years in the Department of Hydraulic Structures (Civil Engineering) where he gained experience in structural and numerical analysis. During this period he also achieved several experimental tests in the hydraulic laboratory and towing tank. Since 1991 he has been an ISSC Committee Member working mainly on ultimate strength.

Dr. Enrico Rizzuto is an Associate Professor in Ship Structural Design at the Department of Naval Architecture and Marine Technologies (DINAV) of the University of Genoa since 2001. He obtained his Honors Degree in Naval Architecture and Marine Engineering in 1986 from the University of Genoa. He served three years at CETENA (the Italian Ship Research Center) in the Hydrodynamic Department, where he gained experience in the design of propellers and in their verification as regards hydrodynamic performance, induced pressures and radiated noise. During this period he was also responsible for the development and analysis of a few contractual sea trials of commercial and naval ships. In 1990 he joined DINAV as Researcher. In 1993-94 he obtained a grant funded by the European Union for a I-year research program, developed at the Royal Institute of Technology (KTH) in Stockholm (Sweden). He is responsible at DINAV for several research contracts awarded within International and National research programs or funded by major Research Centers, Shipyards and Manufacturers in the shipbuilding field, covering theoretical and experimental definition of quasi-static, dynamic and impulsive loads acting on ship structures and of inherent responses; vibration and noise propagation on board ships; reliability evaluation of ship structures and plants. He is a member of ISSC 2000 (Committee VI. 1: Extreme Hull Girder Loading) and of ISSC 2003 (Committee VI. 1: Fatigue Loading)

Chapter 19

Professor Bilal M. Ayyub is the General Director of the Center for Technology and Systems Management at the University of Maryland, College Park. Dr. Ayyub completed his B.S.C.E. (1980), M.S.C.E. (1981), and Ph.D. (1983) at Georgia Institute of Technology in Atlanta. He joined the University of Maryland in 1983, and presently is a Professor of Civil and Environmental Engineering at the University of Maryland, College Park. He directed the structures programs and the project management program at the University of Maryland. He is a consultant and board member of two corporations that provide services in the areas of risk and decision analysis. Dr. Ayyub has served the engineering community in various capacities through societies that include ASCE (fellow), ASME (fellow), SNAME (fellow), IEEE (senior member), ASNE (life member), and NAFIPS. Dr. Ayyub received several best-paper, research, and service awards from ASCE, ASME, ASNE and NAFIPS, and is on the editorial boards of professional journals. Professor Ayyub has completed several research projects funded by the National Science Foundation, the U.S. Coast Guard, the U.S. Navy, the U.S. Army Corps of Engineers, the Maryland State Highway Administration, the ASME, and several engineering companies. He is a researcher and consultant in the reliability and risk analysis of engineering systems, and in decision analysis. His publications, which include five textbooks, six edited books, book chapters, refereed journal papers, reports, and papers in conference proceedings, number about 350.

Dr. Ibrahim A. Assakkaf is an instructor of Civil Engineering at the University of Maryland, College Park. He is the director of reliability research at the Center for Technology and Systems Management (CTSM) at the University of Maryland. He completed both his B.S. degree (1990) and M.S. degree (1993) in civil engineering at the George Washington University in Washington D.C., and his Ph.D. degree (1998) at the University of Maryland. Before 1985, Dr. Assakkaf was employed as a general manager for six years by Assakkaf Establishment, a major construction company in Saudi Arabia that was awarded a number of both public and private projects in Saudi Arabia. Dr. Assakkaf's most recent experience was with the CTSM by working on projects funded by the U.S. Navy, University of New Orleans (UNO), and other government organizations to develop Load and Resistance Factor Design (LRFD) for ship structures. Dr. Assakkaf is the author and co-author of 50 papers and reports relating to reliability-based designs and analyses.

Chapter 20

Dr. Volker Bertram is a Professor of Naval Architecture and Offshore Engineering at ENSIETA in BrestlFrance where he teaches ship production and materials, design, seakeeping and ship hydrodynamics. He received his M.S.E. from the University of Michigan, a Dipl.-Ing. and a Dr.Ing. from the University of Hamburg, and a Dr.Ing.habil. from TU Berlin. Industry experience includes work for Mitsubishi Heavy Industries, the Hamburg and Rome ship model basins, and McKinsey & Co. He taught at TU Hamburg-Harburg and Danish Technical University before joining ENSIETA.

Thomas Lamb, See Chapter 1

Chapter 21

Al Horsmon is the Naval Architect for ATC Chemicals Corp. ATC makes structural foam used in sandwich composites, mainly for all different kinds of marine craft. He works with other naval architects, designers, and builders to design composite structures. He received his B.S. in Ocean Engineering from the U.S. Coast Guard Academy in 1976. He served in the Coast Guard as a shipboard engineer, then as a marine inspector before attending graduate school at the University of Michigan where he received Masters Degrees in Naval Architecture and Marine Engineering, and in Mechanical Engineering in 1984. He then worked at Coast Guard Headquarters where he analyzed casualties and wrote decisions on materials applications, including NVIC 8-87 on Fiberglass. Since coming off active duty in 1988, he has remained in the Reserves, worked as a researcher at the University of Michigan, as an independent consultant to the marine industry, and as a technical representative to TORIN, then Airex and now ATe. He joined ATC full time in 1999.

Chapter 22

Hans Hofmann is a Program Manager of AMSEC LLC - M. Rosenblatt & Son, Washington Operations. He recently completed the successful design of the surface portion of the USCG Deepwater project as a member of the Lockheed Martin-Northrop Grumman Team. He also was the Program Manager for the design of the U.S. Navy T-AO 187 Class Oiler Design. He served a 3-year apprenticeship at Stue1cken Shipyard in Hamburg, Germany that began in 1950 and completed his education in 1957. He is a member of the Society of Naval Architects and Marine Engineers, the American Society of Naval Engineers and the USCG SOLAS Working Group. He has published papers on Design for Producibility, Impact of Double Hull on Tanker Design and Design of Floating Dry Docks.

Thomas Lamb, see Chapter 1

Chapter 23

Michael Shimko is the Manager for Materials Engineering of AMSEC LLC - M. Rosenblatt & Son, Washington Operations. He received his B.Sc. (Chemistry) from the University of Maryland in 1977 and his M.Sc. (Mechanical Engineering) from the Naval Postgraduate School in 1983. He completed a 17-year career, as an Engineering Duty Officer in the United States Navy in 1994, which started as his assignment as a material and division officer onboard the conventional-powered aircraft carrier *USS'Forrestal* (CV 59). He has experience in both public and private shipyards, and served as the Deputy Director for Materials Engineering at the Naval Sea Systems COmQIand in Washington, De. Additionally, he served as a Mechanical and Materials Engineering instructor at the United States Naval Academy. Since his active-duty tour in the Navy, he has been employed by AMSEC LLC where he is currently the Manager for Materials Engineering. He is a registered Professional Engineer in Pennsylvania, NACE International certified Materials Selection and Design Specialist, as well as a Corrosion Specialist. He is a member of American Society of Naval Engineers (ASNE) and NACE International.

Miles Kikuta is the Deputy of AMSEC LLC - M. Rosenblatt & Son, Washington Operations. He received his B.Sc. (Electrical Engineering) from Illinois Institute of Technology in 1974 and his M.Sc. (Mechanical Engineering) and Ocean Engineer degrees from Massachusetts Institute of Technology in 1984. He completed a 20-year career as a Surface Line Officer and Engineering Duty Officer in the United States Navy in 1994. His assignments included tours on board USS *Jouett* (CG 29) as the Damage Control Assistant, instructor at the Surface Warfare Officer School, a ship superintendent at a public shipyard, Assistant Program Manager for Aircraft Carrier Service Life Extension Program in the Naval Sea Systems Command (NAVSEA) and Deputy Director, Materials Engineering Group in NAVSEA. Upon his retirement from the United States Navy, he has been employed by AMSEC LLC where he has managed the Materials Engineering Group, the Fluids Group, and the Marine Engineering Division. He is currently the Deputy of Washington Operations, focusing on NAVSEA tasks and projects. He is a member of the American Society of Naval Engineers and NACE International.

Chapter 24

Professor Emeritus Alan Rowen retired from Webb Institute of Naval Architecture in 2001 and assumed his current position as Technical Director ofthe Society of Naval Architects and Marine Engineers (SNAME). Professor Rowen taught at Webb Institute for almost 25 years, and was the first Rosenblatt Professor of Marine Engineering. After graduating from the State University of New York Maritime College in 1965 he sailed on merchant ships as a watchstanding engineer, later returning to the Maritime College as an Engineering Watch Officer and Instructor. Subsequently he then joined the Naess Shipping Group, moved to London as Manager of New Construction, but returned to New York in 1977 to the post at Webb Institute. While at Webb Prof. Rowen worked as a research associate and as an independent consultant. He contributed to a number of publications that are widely used in the industry, and by students at Webb Institute and at other schools. He is a Life Fellow of SNAME, and chaired the Society's Ships' Machinery Committee. He is also a Fellow of the Institute of Marine Engineers and an officer of the Institute's Eastern USA Branch.

Chapter 25

Mark Spicknall is an Assistant Research Scientist within the University of Michigan's Department of Naval Architecture and Marine Engineering. His research focuses on developing and. deploying methods and tools for strategic and product planning, production engineering, production planning, scheduling, and control, quality management, cost estimating, technology management, and business risk analysis. In addition to collaborative industry research, Mr. Spicknall has significant practical shipbuilding experience having worked at Newport News Shipbuilding for several years in a variety of operations management positions. He is a former editor of the *Journal of Ship Production* and remains a member of SNAME's *Journal of Ship Production* Committee. He is also a member of the Shipyard Production Process Technologies Panel of the National Shipbuilding Research Program. Mr. Spicknall has a B.S.E. in Naval Architecture and Marine Engineering and an MBA, both from the University of Michigan ..

Chapter 26

Thomas Lamb, see Chapter I

Chapter 1

Introduction

Thomas Lamb

1.1 THE PURPOSE OF THIS BOOK

The purpose of this book is to:

- assist ship designers and shipbuilders make better design decisions by providing the required knowledge in one relatively easily accessible source,
- provide a book that can be used by naval architecture students to learn about ship design and construction, and
- serve as a reference when they enter the marine industry.

It is also hoped that the coverage of the book will be of interest to those who seek an authoritative reference in this field.

1.2 NEED FOR INTEGRATION

The successful practice of shipbuilding is not only a design matter, but depends on the integration of marketing, design, procurement, production, and the business functions such as finance and human resources.

Naval architects need to have a basic understanding of all of them to be effective and successful in their careers. New approaches such as *Concurrent Engineering* (CE), *Integrated Product and Process Development* (IPPD), and *Integrated Product Teams* (IPTs) have been developed to ensure that all areas impacting design decisions are considered, and *Systems Engineering* (SE) has been developed to ensure that the isolated specialist solutions are integrated. These are addressed in Chapter 5 - The Ship Design Process.

The naval architect has the education and training to fully understand the implications of ship design trade-off decisions and should always be the integrator or systems engineer for ships.

1.3 GLOBALIZATION

Shipbuilding has always been global in that the ships built in one country may be for a shipowner from another country and trade worldwide. Even the materials to construct the ship could come from many countries, such as steel from Norway, diesel engine from Denmark, propellers from Britain, and bridge consoles from U.S. for a ship being built in Spain.

Even the ship design has been global in that design agents in one country could design a ship to be built in another, such as designed in Canada and constructed in China. While some shipowners prefer to build in their own country, the price to do so may be prohibitive and the shipowner may be forced to build in the country with the lowest prices in order to stay competitive in the shipping market.

However, shipbuilding is not a true *free market* in that many countries support their shipbuilding industry through direct and indirect (sometimes hidden) subsidies. Currently, Korea is the price setter and is pricing well below the actual cost to construct ships in many other countries. Some developing countries choose shipbuilding as a way to develop an industrial base and also to provide a positive element to their balance of payments. The technology is easily transferable, and, at the fabrication level, it does not require a high level of education or skills with high productivity, if the country's labor and/or exchange rate is low compared to other shipbuilding countries. For example, China has very low productivity but this is offset by very low wages.

1.4 WHAT IS DESIGN?

Today, there is still a general lack of understanding of the essence of design. Design is the arrangement of elements that go into human productions. Design is not a body of knowledge. It is the activity that integrates the existing bodies of knowledge, to achieve a given outcome.

Design is a highly manipulative activity in which the designer has to continuously and simultaneously pay attention to and balance many factors that influence the design outcome.

Because of the incompleteness of knowledge at the different design stages when decisions are being made, it is usual to reexamine them at subsequent points in time when more knowledge is developed. This process of reexamination is the iterative nature of design and is recognized as an integral part of the process.

To design is to invent (1).

1.5 DIFFERENCE BETWEEN DESIGN AND ENGINEERING

Engineering is a very misused word. It can be used to describe a profession, the process of developing a design into working instructions, and a type of manufacturing. In this book we will be considering the second case only. One of the earliest definitions of Engineering, from the Charter of the Institution of Civil Engineers is that:

> *Engineering is the art of directing the great sources of power in nature for the use and convenience of man.*

Another idea offered by Dr. S. Erichsen is:

> *Designers create and Engineers analyze.*

Some people see Design as a part of Engineering. In this sense they see that some engineers design and some analyze the design of others. So in this book the following definitions will be used:

> *Design decides all technical matters. This includes the analyses necessary to validate these design decisions. Engineering develops and documents the design to enable its manufacture.*

1.6 WHAT DO WE MEAN BY DESIGN PROCESS?

All activity has a process whether it is formally documented or not. An individual designer may develop a new design process for performing a particular design, but over time it will evolve into a set of preferred steps. Within an industry a few preferred processes are eventually *selected* (best practices) and implemented through documentation, publication, and teaching. Chapter 5 - The Ship Design Process, documents the current process used in the U.S. for naval ship design.

By *Process* we refer to a series of actions or operations leading to an end. *Design process* is interchangeable with *Methodology.* Both process and methodology thus are procedures for completing activities. The procedures are structured, that is they are a step-by-step description and provide a framework or template for the key information and decision-making.

A good process, if followed, will produce an effective design for minimum effort and in the shortest time. Practitioners of ship design have developed this process over many years. The process can be a learning tool thus saving new designers time.

When performed on the computer, this process is blurred by speed, but the process is still there, imbedded in the various programs.

Documented design processes usually have developed over time by trial and error and the best (efficient in effort and duration) is reached by evolution. Some developers of such processes for ship design have presented their processes in technical books and papers.

There are exceptions to the gradual evolution approach including developers who have applied *Systems Engineering* approaches to develop requirements and a solution for the ship design process.

A structured design process permits the designer to develop innovative and creative solutions. Documented design processes provide the following advantages:

- the process is made explicit,
- it is known to everyone, allowing an understanding of the design rationale and reducing the possibility of proceeding with unsupported decisions,
- ensures that important design issues are considered,
- structured processes are largely self-documenting; in the process of executing the process a record of the decisions is created for future reference and for educating new designers, and
- standardization within companies and even industries.

1.7 IMPACT OF COMPUTERS ON DESIGN

Even where there was no process documentation, the use of computers has demanded that processes be developed as a way to define the flow of information. While a user of a design synthesis program may not see or understand the process used by the program, it is there. Because of the speed of computations the computer can perform in a millisecond what took days and even weeks manually. This does not, however, eliminate the need for a process that is efficient in operation.

1.8 DESIGN APPROACHES

The design of a marine vessel or offshore platform brings together the needs and ideas of many functions from the ship operator, shipowner, designer, planner, procurer, and producer. Without proper integration and collaboration, the end product may not satisfy anyone.

In addition, design is a decision-making process. The selection of design parameters is a decision. As with any decision there is usually some level of uncertainty. Designers use knowledge to reduce this uncertainty and thus enable superior decisions.

There are two factors that complicate design decision-making, namely the uncertainty involved in both the inputs and outcomes, and knowing what information (knowledge) must be considered in developing the outcomes from the selected options. A naval architect must be knowledgeable in the many disciplines that are involved in a marine vessel, be it a ship or offshore drilling or production platform. It is the naval architect's responsibility to ensure the integration of all the systems into a successful product.

Mathematical (computer) models are used to reduce uncertainty in design decision-making. Some models provide only a single (deterministic) value for the outcome. Today, this is usually not acceptable. What is needed is a set of outcomes and their probability. The old design spiral has given way to the *Design Option Space* and *Set-based Design.*

Today ship design is seen as a typically multi-disciplinary activity. Because of this, no one person is expected to be equally proficient in all the disciplines involved and this requires the use of what has become known as *Systems Engineering* and teams to accomplish the successful design of any large complex product. Ships are among the most complex products in the world. That this is so can be seen by considering the number of individual parts required for different products as shown in Table 1.1.

Design is a process of synthesis (refining) and integration covering many disciplines. Successful design depends on knowing what information is required, how to get it, and how to use it.

Because of the extent of required knowledge, traditional design is accomplished by dividing the overall product into manageable parts, each of which has a disciplinary focus. Systems Engineering focuses on the relationship of the different systems and disciplines involved in their design and integration of them all, to give the best outcome. Systems Engineering provides a framework, which offers the ability to develop design options and to enable decision-making to make a rational selection of one of the options. To develop a design option space requires two distinctly different activities, namely design synthesis and parametric selection.

The option space may contain too many options for an individual, or even a team of designers to consider every option, although today, modeling and computers increase the number of options that can be considered.

However, often only a small number of the options may be selected for further analysis and even if the best of these is finally selected, it is quite likely that the overall best design or global optimum was not considered.

This means that the selected design was *sub-optimal.* Mathematical methods to find the single optimum solution in the option space are often limited and may also miss,the best option. It is better to have a method to show the outcomes of sets of options from the option space, which contains the best option, rather than have just a single solution. Then the decision-making tools can be applied to all the options and the best one selected.

Chapter 5 describes the ship design process in detail. The following is a general discussion on design approaches.

The design spiral, originated by Professor J. Harvey Evans (2), has been used to describe the preferred ship design process for many years. It is focused on a series of activities that converge, as efficiently as possible, on a single solution to the design requirements of a specific project. This approach often involves making decisions based on incomplete information and/or compromise. Thus, it either requires significant rework (iterations) to reach an acceptable design or acceptance of a design that is not the best.

The *Design Bounding* approach (3) is an alternative design process that uses the option space. It considers a number of ships within a range of values for all dimensions and coefficients, which *bracket* or *bound* the domain space that contains all the solutions. While it involves performing the

TABLE 1.1 Number of Unique Parts in Product

Product Type	*Number of Unique Parts*
Aircraft Carrier	2 500 000
Submarine	1 000 000
VLCC	250 000
Boeing 777	100 000
Fighter aircraft	15 000
Automobile	1000

design calculations for every design combination it avoids the need for iteration, and with the use of computers many calculations can be made very quickly.

In the last decade the *Set-based* design approach, accredited to Toyota, has been offered as the best approach. There are many other concepts proposed in reference 4.

It is because of the iterative nature of many design approaches that the principle of *Least Commitment* should be followed. That is, progressing from step to step in the process, no irreversible decision should be taken until it is necessary. This principle of Least Commitment provides maximum flexibility in each step and the assurance that more alternatives remain available as long as possible, thus permitting the eventual selection of the best alternative. The Policy of Least Commitment has been shown to result in more efficient design, primarily due to the reduced requirement for iteration, since better decisions are being made at each step of the process. This is the goal behind the Set-based design approach.

Set-based design is an alternative approach to the common single design approach where a design is iterated and improved until an acceptable solution is developed. This single iterative design approach was named as *point-to-point design* (5). The problem with this approach is that it is often believed to result in the optimum design, whereas experience has shown that this is not the case. Most design synthesis programs follow this same approach and attempt to converge on an acceptable design.

Set-based design deliberately considers a set of designs that will meet the requirements until all unknowns are determined, and then the best alternative is selected. It is basically a weeding-out process. Set-based design has been shown to provide better design and in shorter time. This is the so-ca~led *Sec~nd Toyota Paradox* in that you appear to do more 10 less time.

Set-based design offers many advantages over the point-to-point design approach, such as:

- traditional design develops one solution to the design requirements and it has no way of knowing if it is a good solution other than experience.
- traditional design optimization evaluates one solution after another in a standard search routine. This approach can be expensive in the number of single designs it evaluates to find the optimum solution, and
- in transportation studies it has been found that the metric curves are relatively flat and that there are many solutions with significantly different characteristics that are almost equally acceptable. The single optimum solution approach ignores these alternatives that may offer other advantages.

Commercial and naval ships have significantly different scopes at the early design stages such as *Concept* and *Preliminary* (see Chapter 5 - Ship Design Process for a discussion on the various types of design and their stages). A Navy Concept Design is even larger in scope than a typical commercial Preliminary Design.

The U.S. shipbuilders/designers, generally, prepare many more documents for *Contract Design* than most other shipbuilding countries. A typical U.S. Contract Design for a commercial ship would consist of up to 40 drawings and 800 pages of specifications. A typical Contract Design for the rest of the world would have 3 to 6 drawings and 10 to 100 pages of specifications, including a Selected Vendor List.

The success of a commercial ship design has always and will always be measured by its economic outcome. That is, was it a financial success for the shipowner as well as the shipbuilder? Ship designers today are being required to oase decisions on cost outcomes. *Target Costing,* the U.S. Navy's *Cost as an Independent Variable, Total Ownership Cost* and *Life Cycle Costing,* are approaches and tools that must be part of the ship designers core skill competencies. Chapter 6 discusses the application of Engineering Economics in ship design.

Another design issue that has developed globally over the past 20 years is *Designfor* X, where X can stand for any and all of Production, Assembly, Manufacture, Maintenance and other construction and service-oriented needs. This book recognizes all these and provides chapters, or information on many of them. Design for Production is covered in Chapter 14 - DesignlProduction Integration.

1.9 SHIP CONSTRUCTION

Block construction and pre-outfitting were a common and necessary practice in the U.S. (6) and U.K., and even in German submarines (7), in World War II. After the war it was still used in U.S. shipyards but not improved. The Japanese developed a higher level of these practices to catapult them into world shipbuilding leadership. This development is described in Chapters 25 - The Shipbuilding Process and 26 - Shipyard Layout and Equipment.

CAD/CAM/CIM both provides and drives the need for dimensional accuracy, which in turn enables the application of robotic assembly and welding. Computer applications in ship design and shipbuilding are described in Chapter 13 - Computer Based Tools. Processes such as plasma cutting, high-pressure water jet cutting, one side welding, automation for panel lines and pipe shops, robotic profile and pipe fabrication are discussed in Chapter

26 - Shipyard Layout and Equipment. The handling of material and work in progress has also seen significant improvement and innovation.

1.10 PRODUCTION ENGINEERING

The term *Production Engineering* has many different meanings in different companies. Its purpose is to eliminate inefficient design and methods. In its most basic use it is the engineering that is performed to prepare the information and documentation required by the Production Department to enable them to plan, schedule, construct, and test the ship, boat or, offshore platform.

In the past, because the manner in which the technical documentation was prepared by the Engineering Department was, in some cases, not suitable for direct use by the production workers, a separate group was formed to develop the required production documentation. This group also was often given the task of developing the work packages, which could involve process analysis, shop planning, scheduling, and production and material control.

In this book use of the term Production Engineering will follow the basic meaning as presented in Chapters 5 - The Ship Design Process and Chapter 14 - DesignJProduction Integration.

Production engineering principles include:

- alignment of design, production engineering, production process, facilities and tooling,
- standard range and type of interim products,
- integration of steel and outfit design,
- design for self-aligning assembly,
- design for workstations, and
- simple and robust systems architecture and arrangements, and reduced material and labor content.

Production engineering tools include:

- group technology,
- shipbuilding policy and build strategies,
- trade-off analysis,
- parametric analysis,
- concurrent engineering,
- elemental cost analysis, and
- shipyard standards.

1.11 ROLE OF NAVAL ARCHITECT

The role of naval architects is both wide and focused. It obviously depends, to some extent, on the segment of the industry in which they choose'to work. However, whatever it is, it is usually in a leadership role. That they are able to fulfill this leadership role is a reflection of the useful breadth as well as specialization of the education and eventual experience gained in the industry.

Naval architects are found in many positions in the marine industry. Table I.II shows the industry categories in which they can be found and Table I.III lists typical positions. It can be seen from the tables that the role of naval architects offers many interesting challenges and opportunities for a satisfying and rewarding career in the marine industry.

TABLE 1.11 Industry Segments in which Naval Architects Work

Shipowner
Design Agent
Shipbuilder
Boat Builder
Government
• USCG
• Department of Transportation
• Navy
• Army Corps of Engineers
• Research Centers
Classification Societies
Education (universities)
Independent research centers
Marine equipment manufacturers

TABLE 1.11I Positions for Naval Architects

Shipowner's Technical/Design Manager
Design Agent Executive
Shipyard Executive
Chief Naval Architect
Naval Architect
Project Manager
Technical Project Manager
Technical Manager
Ship Manager

1.12 SKILLS NEEDED BY NAVAL ARCHITECTS

A naval architect needs to be educated in all the topics required in the design and construction of ships and other marine products. In addition, the ship designer must have a basic understanding of most of the engineering discipline topics as well as some business. The educational requirements for naval architects can be obtained by looking at the course curricula for the various universities that offer degrees in naval architecture.

Although there are some differences, the traditional naval architecture topics include:

- Theoretical Naval Architecture
- Hydrodynamics
- Marine Structural Design and Analysis (Chapters 17, 18, and 19)
- Materials (Chapter 20)
- Welding (Chapter 20)
- Mass Properties (Chapter 12)
- Ship Motions
- Ship Design Theory (Chapter 5)
- Ship Design Practice (Chapter 11)
- Shipbuilding Practice (Chapters 14, 25, and 26)
- Planning and Scheduling (Chapter 25)
- Eng!n~ering Eco~~mics (Ch~pter 6)
- Statistics, Prob~blhty, a~d RISk
- Product Modehng Practice
- Computer Based Tools (Chapter 13)

Other tOpICSmc 1u de:

- The Marine Environment (Chapter 2)
- The Marine Industry (Chapter 3)
- Ship Acquisition (Chapter 4)
- Shipowner's Requirements (Chapter 7)
- Regulatory and Classification Requirements (Chapter 8)
- Contracts and Specifications (Chapter 9)
- Cost Estimating (Chapter 10)
- Human Factors (Chapter 15)
- Safety (Chapter 16)
- Composites (Chapter 21)
- Corrosion and Preservation (Chapter 23)
- Marine Engineering Considerations (Chapter 24)

Most of these are covered at least at an introductory level in this book. Those that are not covered or only briefly addressed can be studied and understood from many other books (most of which are referenced in this book), such as the *SNAME Principles of Naval Architecture and Marine Engineering,* as well as the transactions from the marine technical professional societies.

1.13 SAFETY

Ship designers are involved in designing a product that must be completely self-sufficient while it can be thousands of miles from any other direct support and may have to remain so for weeks and even months. This has demanded a keen understanding of the need for safety and it is at the furefront of many of their actions, even before the imposition of international and/or national safety laws.

Notwithstanding this basic focus on safety there have been unintentional lapses with often catastrophic results, such as large loss of life at sea and pollution of the environment. In some cases the abuse of shipowners resulted in laws that had to be applied by ship designers, such as the original *Plimsoll Mark* to limit the loading of ships.

Today the major body legislating safety in the marine industry is the International Marine Organization (IMO), which is a branch ofthe United Nations. Chapters 8 - R~gulatory and Classification Requirements and 16 - Saf~ty, discuss this organization as well as other regulatory and classification requirements.

1.14 HUMAN FACTORS

Today, it is unacceptable to design any product without considering its interface with humans not only in the operation of the product but also in its manufacture. Human Factors (HF) is discussed in Chapter 15 - Human Factors in Ship Design. The focus on reduced manning for ship crews is based on HF research and analysIs. Human Factors are also part of recent IMO regulations as an attempt to improve safet~ ~t sea through improved design of ships and training of ShIP screw.

1.15 RISK

A major development since the publication of the previous edition of this book is the use of statistics and probability in design and for risk assessment in all aspects of design and operation.

Though relatively new to marine applications, risk analysis and other risk techniques have been used in other industries for more than 50 years. It obtained its impetus from the start of entirely new industries such as nuclear power generation and the U.S. space program. Then it was applied to the protection of the environment and most recently to the safety in the operating of all types of products.

All these cases shared the same problem in that there was no historical data on which to base design/operating decisions, or to predict the performance of equipment relative to its safe operation.

In order to deal with this situation the designers/operators turned to the application of probability to find solutions. Techniques such *asfault tree analysis* were developed to break down the problem into parts that could be analyzed and assigned individual probability levels, which would then be combined into an overall risk assessment.

The old way to design for uncertainty and to eliminate risk of failure was to apply *safety margins* to the derived requirements. The problem is that safety margins are built on experience and where there is no experience *safe* (large) safety margins have to be applied which is a waste of resources and may be cost prohibitive.

After its initial development, the application of risk analysis expanded into indu~tries wher~ the rate of new. technology development was hIgh, or the nsk of catastrophIC or very serious outcomes was present. In some cases it was only brought into use after significant accidents occurred, such as the *Exxon Valdez* cargo oil spill in Alaska.

So what is risk analysis and management?

Risk analysis is *the derivation and evaluation of an adverse (undesirable) outcome of some activity or process.* The foundation of risk analysis is probability. *Probability* is *the likelihood of an event occurring expressed mathematicaliy as a value ranging from 0 to* 1.

In the case of the current focus, it can be seen as the risk of not achieving the contract speed on trials or deadweight for a ship, the risk of structural failure, the risk of an oil spill, the risk of collision in a crowded sea lane, and so on. Probabilistic approaches in ship design now cover subdivision, damage stability, oil outflow, structure (see Chapter 19 - Probability-based Design), machinery monitoring and control, maintenance and operation.

Risk assessment is *the measurement of the risk in a specific problem.*

Risk management (sometimes called mitigatIOn) is *the use of risk analysis to identify ways to reduce the identified risk (s).*

For further informatlOn on nsk analysIs and management in general see references 9-11, and for risk analysis of complex engineered systems see chapter 1.5 of reference 9. Another good introduction addressing the marine industry is the special issue of the USCG Marine Safety Council *Proceedings* magazine (12).

The global marine industry was introduced to risk analysis and management through the activities ofIMO. The UK Marine Safety Agency developed a risk analysis and mitigation approach, the *Formal Safety Assessment* (FSA), which is a broad brush approach to identifying major risk areas, analyzing them in turn, developing ways to mitigate the risk, performing a cost-benefit analysis for the proposed solutions, and then deciding on an approach.

Recent areas of risk assessment in the marine industry are the reliability-based structural design (Chapter 19), and the risk analysis of high-speed craft (Chapter 38 - Ferries and Chapter 44 - High Speed Surface Craft).

Based on their respective responsibilities, it is understandable why both the classification societies and the national regulatory services in the marine industry were also early users of the approach.

Today there are a number of computer-based tools to aid in risk analysis and management. Some of these are presented in reference 10.

1.16 ElMICS

The history of engineering (13,14) shows that, in the main, engineers have maintained a high ethical standard in their work. This is also true in the marine world. Both SNAME and ASNE have had a statement of ethics for its members since their beginning and in certain states and countries, registered professional (chartered) engineers (naval architects) also monitor and control the ethical standards of their profession.

Many people believe that the three greatest issues challenging engineers today are in the areas of: ethics, environment, and resources.

Ship designers sometimes find that doing what is right may put them in conflict with the desires of their employers, or if independent, their clients. What should they do in such cases? If not handled properly, their decision could resuIt in damage to their career and their company's reputation, or conversely have a detrimental outcome to society.

Fortunately there are mechanisms in place, such as:

- the legal system,
- state professlOnal laws,
- company procedures, and
- professlOnal SOCIety standards.

The ethical behavior of ship designers is especially important in that it influences the direction of the development of technology in the marine and atmospheric world. The decisions they make have a direct consequence on public safety and the environment and the use of resources.

What does this demand of today's and future ship designers? Must they become legal experts?

Fortunately the answer is no. Most people have an innate ability to know right from wrong, although it can become biased by the opportunity or perception of personal gain. Add to this innate ability, guidelines that can be taught to students and codes that can be presented and managed by their peers, and there is a system for education and control.

In the simplest sense, it requires that the ship designer:

- consider social and environmental impact of all design decisions,
- not become involved in projects that will be harmful to society or the environment,
- not be wasteful of any resource because they are all scarce, and
- make available any of theittechnical data and decisions that may be of public interest, under the appropriate conditions.

Th e ethi cs po Ii cy o fth e S·oclety o fN av alArchi tects an dM arine Engineers is worth study and is as presented in Table 1.N

Another ethics statement worth review is that of the EuropeanAssociation of Engineers (15). A code of ethics can be considered as a collective recognition of professional responsibilities by a group of practitioners. When properly drafted such codes can be of tremendous help in guiding

TABLE l.IV SNAME Code of Ethics

Foreword

Engineering work continues to be an important factor in the progress of civilization and the welfare of the community. The Engineering Profession is held responsible for the planning, construction and operation of such work, and is entitled to the position and authority that will enable it to discharge this responsibility and to tender service to humanity. Honesty, justice and courtesy form a moral phil\osophy that, associated with the mutual interest among peoples, constitutes the foundation of ethics. As professionals naval architects and marine engineers should recognize such standards, not by passive observance, but as a set of dynamic principles to guide conduct.

Fundamental Principles

Naval Architects and Marine Engineers should maintain and advance the integrity, honor and dignity of their professions by:

- using their knowledge, experience and skill for the enhancement of human well-being and as good stewards of the environment,
- striving to increase the competence of the professions of naval architecture and marine engineering, and
- being honest and impartial, and serving with fidelity the public, their employers and clients.

Specific Canons

Naval architects and marine engineers shall:

1. Carry on their professional work in a spirit of fairness to employees and contractors, fidelity to clients and employers, loyalty to their country, and devotion to the high ideals of courtesy and personal honor.
2. Hold paramount the safety, health and welfare of the public in the performance of their professional duties. They will interest themselves in the public welfare, in behalf of which they will be ready to apply their special knowledge, skill and training for the use and benefit of mankind.
3. Refrain from associating themselves with, or allowing the use of their names by, any enterprise of questionable character.
4. Advertise only in a dignified manner, being careful to avoid misleading statements.
S. Regard as confidential any information obtained by them as to the business affairs and technical methods or processes of a client or employer.
6. Inform a client or employer of any business connections, interests or affiliations that might influence their judgment or impair the disinterested quality of their services.
7. Refrain from using any improper or questionable methods of soliciting professional work and will decline to payor to accept commissions for securing such work.
8. Accept compensation, financial or otherwise, for a particular service, from one source only, except with the full knowledge and consent of all interested parties.
9. Build their professional reputations on the merits of their services and shall not compete unfairly with others.
10. Perform services only in the areas of their competence.
11. Cooperate in advancing the professions of naval architecture and marine engineering by exchanging general information and experience with their fellow naval architects and marine engineers and students, and also by contributing to the work of technical societies, schools of applied science and the technical press.
12. Continue their professional development throughout their careers and shall provide opportunities for the professional development of those naval architects and marine engineers under their supervision.

requisite knowledge and the behavior of its participants. Its principal use is a guide to behavior when its adherents are faced with the many decisions in their work.

The licensing of engineers (Professional and Chartered) is an attempt to control behavior and thus ethics. The State Professional Engineering newsletters have many references to disciplinary action taken by the State for professional engineers who violated their laws.

1.17 PUTTING IT ALL TOGETHER

Even if a person is knowledgeable in all the areas covered by this book and the many references contained herein, it does not mean that they will be able to successfully complete a major design project, because such an activity requires additional skills and knowledge.

As stated in the preface the most important skill is knowing:

- what must be done,
- how it should be done
- what knowledge is required, and
- how to get the required knowledge.

This is in effect *Ship Design Management.* The management of ship design is not directly addressed in the book, but some of the knowledge it requires is discussed. Chapter 5 - The Ship Design Process, is the only chapter directly addressing the first two of the stated needs. The third need is covered throughout the other chapters in the book, and the final need is addressed by providing state of the art knowledge plus references where even more information (knowledge) can be acquired for specific ship types in Volume II.

It is therefore hoped that this book will be of significant help in acquiring this important skill.

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Chapter 2

The Marine Environment

Guy A. Meadows and *Lorelle A. Meadows*

2.1 THE WORLD'S WATERWAYS

The oceans, navigable lakes, inland seas and rivers of the world comprise slightly over 72% of the earth's surface. These world waterways are extremely important to national and international commerce, with approximately 95% of all goods being transported by water. Oceans, lakes and rivers are characteristically broad and relatively shallow with extremely large aspect ratios (the ocean being equivalent in aspect ratio to a piece of loose leaf paper). Hence, it should be anticipated from an applied ocean physics point of view, that stresses acting upon both the surface and bottom boundaries of these basins should control the dynamics of their circulation, motion, and internal structure. Fluxes of momentum, mass, and heat across these boundaries (surface, edges, and bottoms), are largely responsible for the internal dynamics, which result in motion in the marine environment.

2.1.1 Oceans

The world's oceans collectively comprise approximately 72% of the earth's surface area. The ocean can be divided into three primary basins, the Pacific (33% of the earth's surface area), the Atlantic (16%) and the Indian (14%). Smaller seas such as the Baltic, Bering, Caribbean, Mediterranean, and North Seas, as well as the Sea of Japan and the Gulf of Mexico occupy the remaining 9% of the aquatic surface area. A valuable summary of the area of the major ocean basins and marginal seas is presented in Table 2.1.

The geographical distribution of this ocean area is heavily skewed toward the Southern Hemisphere. This produces an excess concentration of landmass in the Northern Hemisphere and a correspondingly large ocean mass in the Southern Hemisphere. Figure 2.1 demonstrates that the surface of the earth can be divided into a *land hemisphere* with its pole centered in France (47% land and 53% water) and a *water hemisphere* with its pole near New Zealand (90% water and 10% land).

The vertical distribution of landmass and ocean basin is also asymmetric. The mean elevation of land above present day sea level is only approximately 840 meters. Of this region, the continental plateau, which accounts for approximately 20% of the land portion of the earth's surface, is at an elevation of only 270 meters. Similarly, within the oceans, the deep-sea bottom, *abyssal plains*, occurs at a depth of approximately 4420 meters, while the mean depth of the sea is approximately 3800 meters.

Hence, the volume of continental landmass above present sea level is less than one tenth of the volume of the oceanic waters. Alternately, the mean sphere depth, or the mean elevation of the entire earth, is located 2440 meters below current sea level. Hence, water would cover the earth to this depth if we resided on a purely spherical planet.

A typical cross-section of an oceanic margin is presented in Figure 2.2. The continental shelf is a nearly flat plain immediately adjacent to the shore. The bottom here slopes gently at an angle of about 0.5 degrees. The width of this terrace ranges from a few kilometers along the Pacific coasts of the Americas to more than 1000 kilometers in the Arctic. The sea bottom steepens appreciably at the shelfbreak, typically at about 130 meters of water depth. At this point, the bottom slope increases to 1 to 4 degrees. Seaward of the shelfbreak is the continental slope, where the 4 degree bottom slope is maintained over a horizontal extent of approximately 50 kilometers. The continental slope is the site of the submarine canyons of the oceans. These canyons have steep sides, V-shaped profiles and vertical relief of up to 2 kilometers, making them one of the deepest landforms on earth. The continental rise-is a long shallow sloping approach to the deep abyssal plains of the ocean. It may extend for more than 500 kilometers where bottom slopes flatten out to approximately 1 degree. The deep, almost flat and featureless Abyssal Plains exist at depths of approximately 3000 to 6000 meters and separate continental margins from mid ocean ridges in most basins. Mid ocean ridges are volcanic mountain chains on the sea floor with relatively steep slopes and rugged topography. They can be of sufficient elevation above the deep ocean floor to provide significant impediments to ocean circulation and exchange between basins.

TABLE 2.1 The Approximate Physical Characteristics of the Major Ocean Basins and Marginal Seas

Body of Water	*Area* (10^6 *km*^{2})	*Depth (m)*
OCEANS		
Pacific Ocean, proper	165	4280
Pacific Ocean, including adjacent seas	180	4030
Atlantic Ocean, proper	82	3870
Atlantic Ocean, including adjacent seas	105	3330
Indian Ocean, proper	73	3960
Indian Ocean, including adjacent seas	75	3900
LARGE MEDITERRANEAN SEAS		
Arctic Ocean	9:5	1530
East Asian Seas	6.0	1210
Caribbean and Gulf of Mexico	4.4	2170
Mediterranean and Black Seas	3.0	1460
SMALL MEDITERRANEAN SEAS		
Hudson Bay	1.23	130
Red Sea	044	490
Baltic Sea	0.42	55
Persian Gulf	0.24	25
MARGINAL SEAS		
Bering Sea	2.27	1440
Okhotsk Sea	1.53	840
East China Sea	1.25	190
Japan Sea	1.01	1350
North Sea	0.58	94
Gulf of St. Lawrence	0.24	130
Gulf of California	0.16	810
Irish Sea	0.10	60
Bass Strait	0.07	70

2.1.2 Lakes

Many of the large lakes of the world are navigable and support immense ship-borne commerce. The North American Great Lakes, comprised of Lakes Superior, Michigan, Huron, Erie, and Ontario, are perhaps the best known of such systems (Figure 2.3). This vast "inland sea" system spans more than 1200 kilometers from west to east and forms the largest fresh surface water basin on earth.

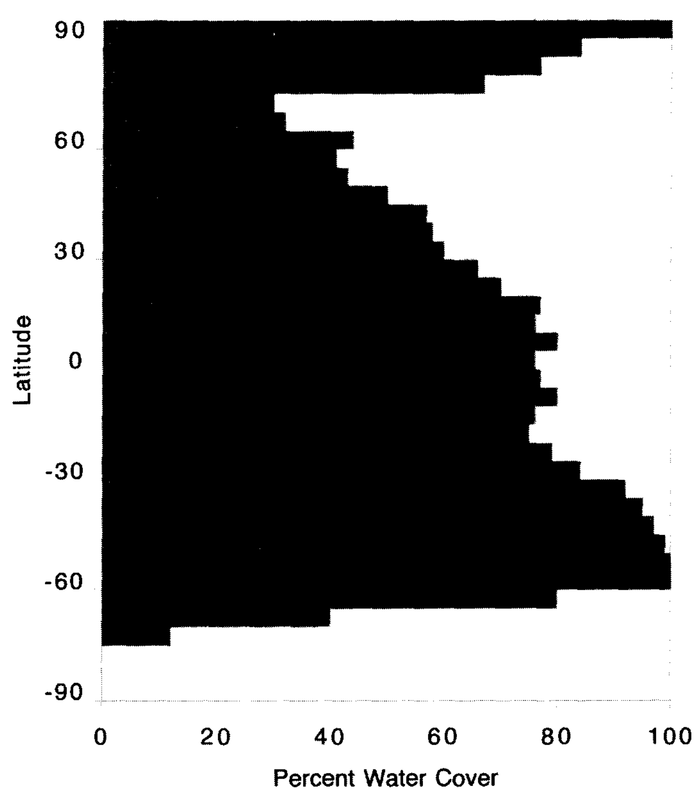


Figure 2.1 Longitudinal Distribution of Land and Sea (Gray region represents sea)

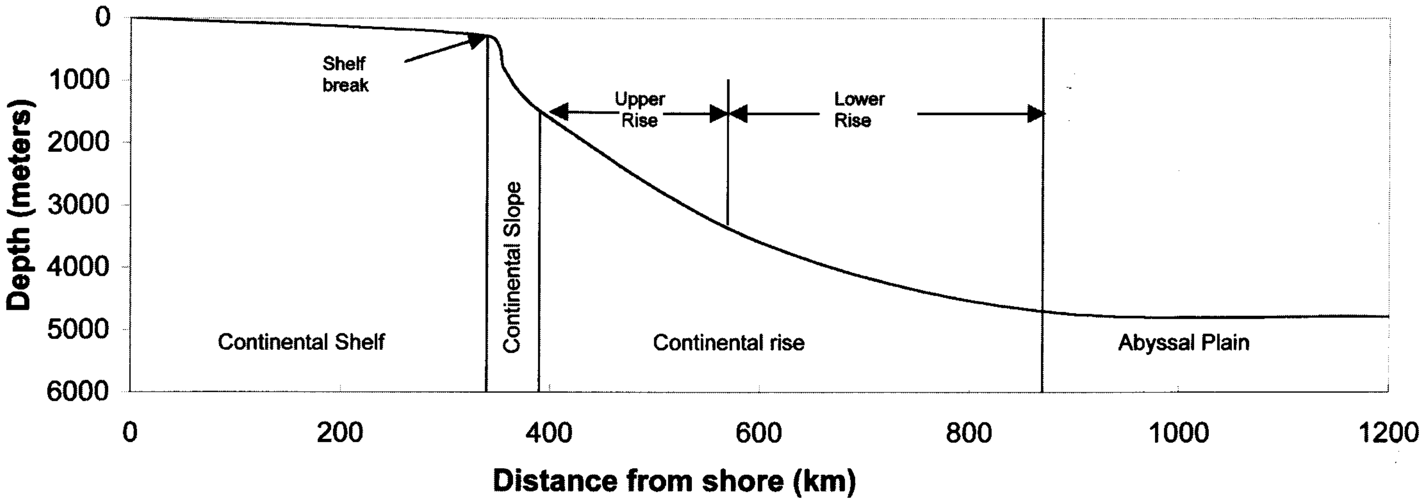


Figure 2.2 Typical Cross-Section of an Oceanic Margin

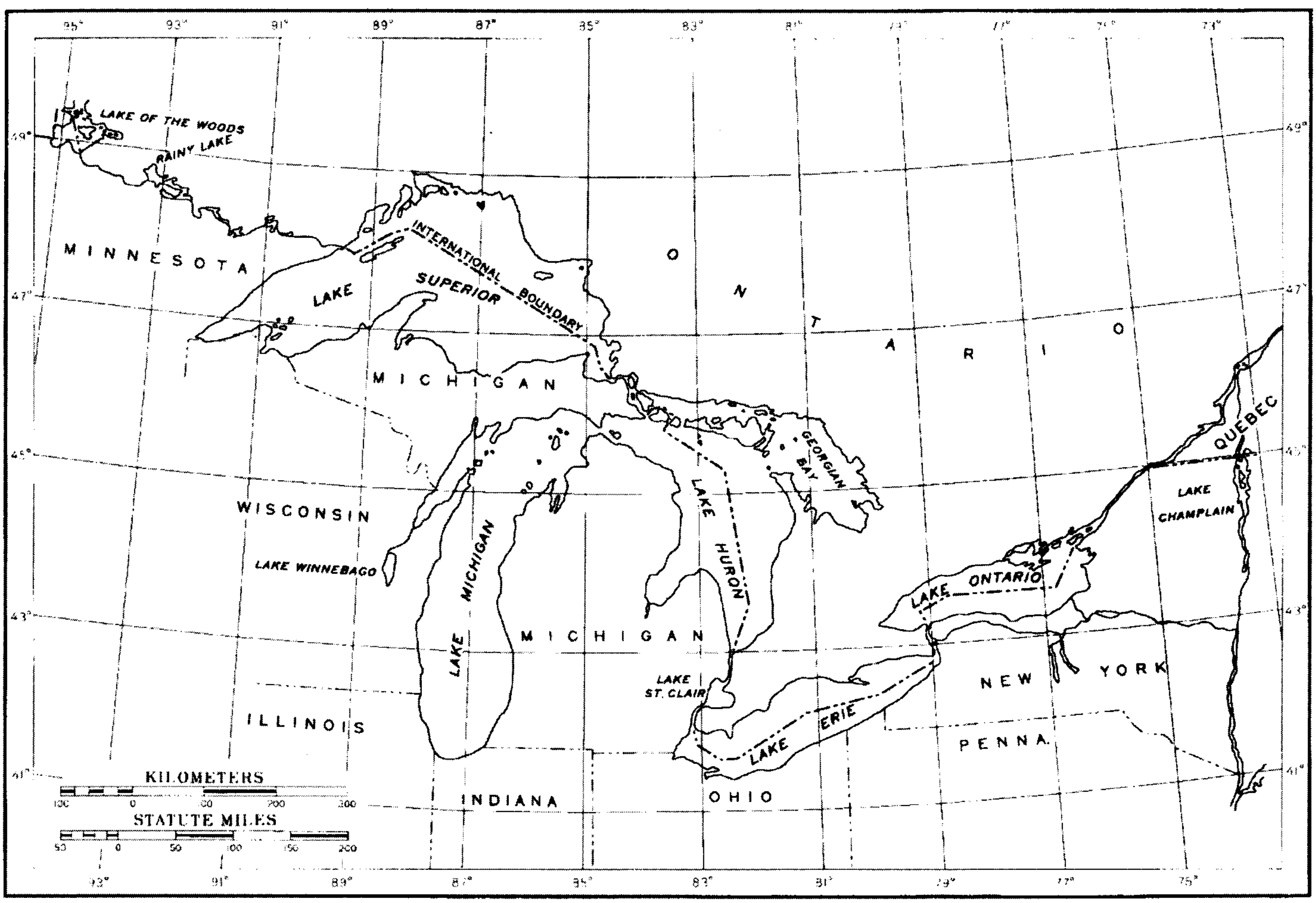


Figure 2.3 The North American Great Lakes

In addition to commercial shipping, these freshwater seas also provide water for consumption, transportation, power, recreation and a host of other uses, see Government of Canada and U.S. Environmental Protection Agency (1).

The connecting channels of the Great Lakes are an important component of this system. The connecting channels are composed of a 97 kilometer waterway flowing from Lake Superior to Lake Huron. The St. Mary's River drops from the surface elevation of Lake Superior at 183 meters above sea level to that of Lakes Huron and Michigan (176 meters above sea level). The St. Clair and Detroit Rivers connecting Lake Huron to Lake Erie drop a corresponding 3 meters over their combined length of 143 km. The Niagara River falls an additional 99 meters between Lakes Erie and Ontario over its short 56 km run. Finally, the St. Lawrence River completes the system and the journey to the sea by falling the remaining 74 meters over its approximately 2600 kilometer journey. A physical description of the Great Lakes System is presented in Table 2.11.

Navigation in and through the large lakes of the world is often complicated by drastic environmental effects, including severe and rapidly developing wind-generated seas, with significant wave heights in excess of 10 meters. Environmental effects also include a variety of secondary wind effects such as large wind driven oscillations of these enclosed basins. Water elevation differences between opposite ends of Lake Erie have been recorded in excess of 4.8 meters. These hydrologic forces can cause momentary current reversals in the connecting channels as well as significant nearly "instantaneous" waterlevel changes. During the winter months in these mid-latitude seas, the formation of both shore fast ice as well as ice floes produce another significant challenge to shipping. Hence, by international agreement the Great Lakes system is closed to shipping between January 15 and spring "break out" on March 15.

2.1.3 Rivers

Navigation and marine construction in rivers often poses unique and challenging engineering problems. In addition to the obvious physical conditions of varying flow rates, seasonal migration of bottom features, periodic dredging requirements, debris, constricted navigation channels and varying water levels, rivers often offer new challenges as well. On the positive side, they have historically provided safe refuge from the sea as well as convenient access to land based facilities and transportation routes. In recent history, contaminants, both living and non-living provide a special level of concern for the contemporary Naval Architect and Marine Engineer.

For example, the spread of non-indigenous species through vessel ballast water exchange is of worldwide concern. During vessel operations in "fresh" river systems, organisms and contaminants can easily be spread by the enormous ballast water exchanges of typical modern vessels. In riverine environments, large suspended sediment concentrations can lead to the introduction of abrasive materials into pumping systems and the eventual accumulation of large quantities of material in ballast tanks. For a more complete description of this problem, see National Research Council Committee on Ships' Ballast Operations (2).

Typical open ocean seawater density is 1026.95 kg/m^3 (ocean water at a salinity of 35 parts per mil or *%0*, temperature of 10° C and at atmospheric pressure). Freshwater at the same temperature and pressure has a density of 1000 kg/m^3. Hence, a 2.7% change in density should be an-

TABLE 2.11 Physical Dimensions of the Great lakes as Modified from *The Great Lakes Atlas* (1)

		Superior	*Michigan*	*Huron*	*Erie*	*Ontario*	*Totals*
Elevation"	(m)	183	176	176	173	74	
Length	(lan)	563	494	332	388	311	
Breadth	(lan)	257	190	245	92	85	
Average Depth"	(m)	147	85	59	19	86	
Maximum Depth"	(m)	406	282	229	64	244	
Volume"	(lan^3)	12 100	4920	3540	484	1640	22 684
Water Area	(lan^2)	82 100	57 800	59 600	25 700	18 960	244 160

" Measured at Low Water Datum.

ticipated when traveling from seawater into a fresh water region. Hence, vessel displacement will also vary by this amount (2.7%). A vessel drawing 10 m at sea will draw 10.27 m in a freshwater environment. Care must be exercised in this transition.

2.2 IMPORTANT FLUID PROPERTIES

Water, salt, ice, and air are the four major constituents of importance in the marine environment. The water, which composes approximately 96.5% of the fluid filling the ocean basins (normal ocean dissolved "salt" content is approximately 3.5% or *35‰*), is perhaps the most unique substance on the planet. It has amazing physical and chemical properties, which have resulted not only in the development of life on this planet, but have allowed this fluid to become the major transport medium of our world's commerce. Water is:

- highly incompressible,
- has an extremely large heat capacity and thermal conductivity,
- is largely opaque to the transmission of electromagnetic energy, particularly in the visible part of the spectrum, and
- is almost totally opaque to the transmission of electromagnetic energy in the radio and radar frequency part of the spectrum.

Freshwater and seawater are both, however, extremely transparent to acoustic energy providing an extremely valuable mechanism for both long range interrogation as well as communications through this fluid medium.

2.2.1 Fresh Water

Perhaps one of the most unique properties of fresh water is its density dependence upon temperature. Above approximately 4°C water behaves as a normal fluid, expanding when heated and contracting when cooled. However, between approximately 4° C (the temperature of maximum density offresh water) and 0° C (the phase change point for fresh water between liquid and solid) water expands when cooled and contracts when heated, thus producing a point of maximum density at approximately 4° C. This temperature of maximum density results in the potential for density driven circulation patterns primarily-during the spring heating and fall cooling periods of large fresh water bodies, such as the Great Lakes. At the point of phase change, approximately 0° C, water undergoes a significant structural change into the ice crystal lattice, producing a 9% increase in volume as the phase change occurs. This increase in volume and corresponding decrease in density allows the solid phase, *ice*, to be less dense than the liquid phase at slightly greater temperature, producing the necessary buoyancy allowing ice to float. If it were not for this peculiar behavior, the oceans and fresh water bodies would freeze from the bottom up, thus resulting in a massively different marine environment than the one to which we have become accustomed.

2.2.2 Salt

As dissolved salts are added to fresh water, peculiar and somewhat unique physical changes occur. The density of water increases with increasing salinity, with the density reaching approximately 1.025 grams per cubic centimeter for normal seawater at a salinity of *35‰* and 20° C. It is interesting to note that both the temperature of maximum density and the freezing point of water decrease with increasing salinity and that the temperature of maximum density decreases at a greater rate than the freezing point. Neumann and Pierson (3) provide the following relationships for the temperature of maximum density, $T_{p_{max}}$, and the freezing point of seawater, T_g, as a function of salinity, S, respectively

$$T_{p_{max}}\ (^\circ C) = 3.95 - 0.200S - 0.0011S^2 \qquad [1]$$

$$T_g\ (^\circ C) = -0.003 - 0.0527S - 0.00004S^2 \qquad [2]$$

These relationships are shown graphically in Figure 2.4. These two lines intersect at a salinity of approximately *24.7‰*, far "fresher" than that of normal seawater *(35‰)*. The implication of this fact is that ice formed from sea water, at salinities of *35‰*, will experience its freezing point at a slightly warmer temperature than the temperature of max-

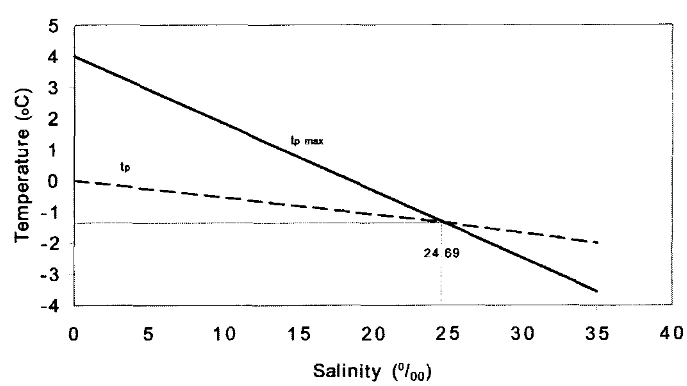


Figure 2.4 The Variation of Temperature of Maximum Density and Freezing Point of Sea Water with Salinity

imum density. This further implies that the temperature of maximum density would occur in the solid (ice) phase, thus hypothetically rendering ice denser than the surrounding fluid supporting it. It is obvious that this does not occur in the real marine environment. This is due to the fact that as the solid phase ice lattice forms, salt ions are precipitated from the ice structure, into the underlying fluid. This process renders the solid phase nearly fresh in salinity, and buoyant relative to its surroundings with anomalously high salinities directly below the forming ice sheet. Since fluid density increases in the marine environment with increasing salinity, these precipitated salt ions form a denser fluid and cause an unstable stratification resulting in vertical, density driven motions (mixing) below the ice sheet.

2.2.3 Ice

The often-rapid loss of heat across the air/sea interface can result in the formation of ice. In the open ocean, ice originates primarily from two sources, sea ice and glacier ice. The formation of sea ice depends upon not only the surface salinity, but also on the vertical distribution of salinity and the water depth.

As shown in Section 2.2.2, at a seawater salinity of approximately *24.7%0,* both the temperature of maximum density and the freezing point correspond at approximately -1.33° C. Therefore, water bodies with a bulk salinity less than *24.7%0* will tend to cool uniformly to the temperature of maximum density for that particular salinity. Continued cooling at the surface results in the development of a thin layer where ice will begin to form once the freezing point is reached. The ice formation process begins earlier over shallow regions and requires longer development time over deeper regions. For water bodies with bulk salinities greater than *24.7%0,* cooling must progress to lower temperatures, again from top to bottom until freezing commences at the surface.

For a detailed description of sea ice conditions and its affect on marine structures, see Chapter 35 of this book.

2.2.4 Air

The flUIdoverlymg the oceans, lakes, and nvers ISair. It has a density approximately 1000 times less than that of water. Under most conditions it is responsible for the transport of enormous quantities of momentum into the sea surface, the exchange of heat out of or into the sea surface, and the extraction of moisture, or mass, from the sea. This interaction is responsible for a major portion of the control of climate on the planet and the intense modification of climate in local communities bordering these bodies of water. The extent to which the oceans and inland seas of the world modify and moderate climate is now only-beginning to be fully understood. There is significant evidence, for example, that the presence of the Great Lakes in the continental interior or North America is responsible for the modification of climate within a region approximately 1600 kIn beyond their boundaries. In addition, the phenomenon known as EI Nino, a region of unusually high ocean surface water temperature off the coast of Peru, plays a significant role in the climate of our planet. The details of air-sea interaction and the ability of the earth's atmosphere to generate both circulation and wave motions on large bodies of water will be more fully examined in Section 2.4.

2.2.5 Density

The salinity and temperature of seawater are important in the marine environment in terms of defining the characteristics of a particular water body and in the determinatiorrof the seawater density, p. Seawater density can range from about 1021.11 kg/m^3 at the surface to 1070.00 kg/m^3 at 10 000 m depth.

As discussed in Sections 2.2.1 and 2.2.2, the density of seawater is dependent upon its temperature and salinity. In summary, the density of seawater decreases with increasing temperature above the temperature of maximum density, and increases with increasing salinity. In addition, the density of seawater increases with increasing pressure.

The vertical water column can be divided into three zones in terms of its temperature structure: an upper zone approximately 50 to 200 m in depth where the temperature is similar to that at the surface, a middle zone where the temperature decreases dramatically from 200 to 1000 m in depth, and a lower zone where the temperature changes slowly. The middle zone is referred to as the *thermocline* and represents a region of rapidly increasing density with depth as well. The depth and gradient of the thermocline varies throughout the world's oceans, but remains a permanent feature in the low and middle latitudes.

2.3 OCEAN OPTICS AND ACOUSTICS

To first order, the equations and principles that describe both the propagation of electromagnetic (light) and acoustic (sound) radiation through the sea are sufficiently similar to warrant a combined approach. It must be noted, however, that electromagnetic propagation is based upon transverse wave theory (particles moving perpendicular to the direction of wave propagation) and acoustic propagation is based upon longitudinal wave theory (particles moving parallel to the direction of wave propagation).

U1 Ocean Optics

As electromagnetic radiation from the sun (for the purposes of our discussion, light in the visible part of the spectrum) passes through the atmosphere of our planet, this energy is absorbed, reflected and transmitted, to varying degrees, through the medium. The degree to which these three processes occur depends upon the wavelength (color) of the light and the composition of the atmosphere. Absorption of incoming solar radiation is mainly attributed to water vapor, carbon dioxide and ozone in the atmosphere. That portion of the incident solar radiation that is absorbed by the atmosphere is transformed into heat and contributes to the heat budget of the atmosphere. Reflection occurs primarily by scattering of solar radiation by air molecules themselves, as well as by airborne dust, water droplets and other contaminants. Similarly, that portion which is scattered by the atmosphere, may reach the earth's surface, 72% of which is covered by water, in the form of diffuse solar radiation. That portion which reaches the earth's surface as direct radiation, transmitted directly through the atmosphere, accounts for approximately 23% of the total incident solar radiation on a global scale.

Figure 2.5 provides a comparison of the spectrum of solar radiation available at the top of the earth's atmosphere

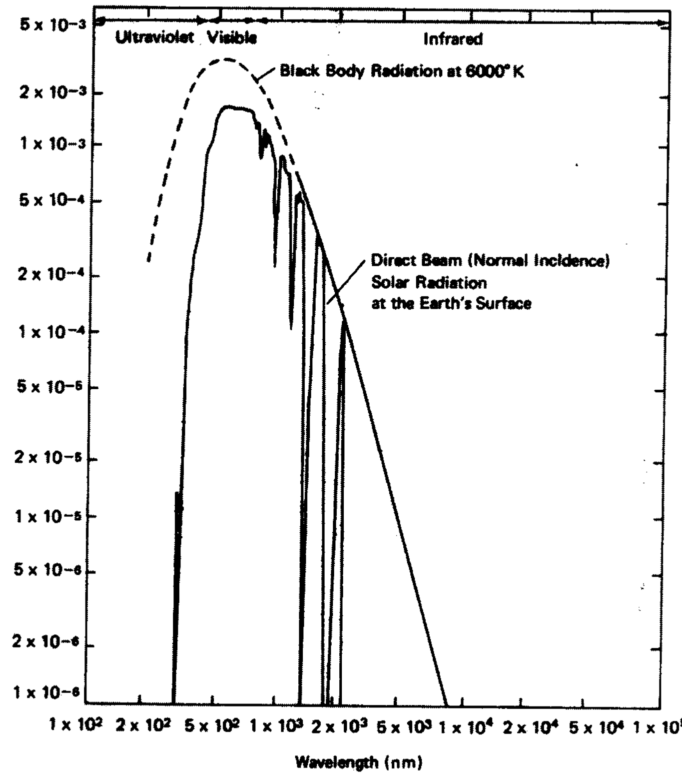


Figure 2.5 The Approximate Solar Radiation Spectrum at the Top of the Earth's Atmosphere and at Sea Surface (4)

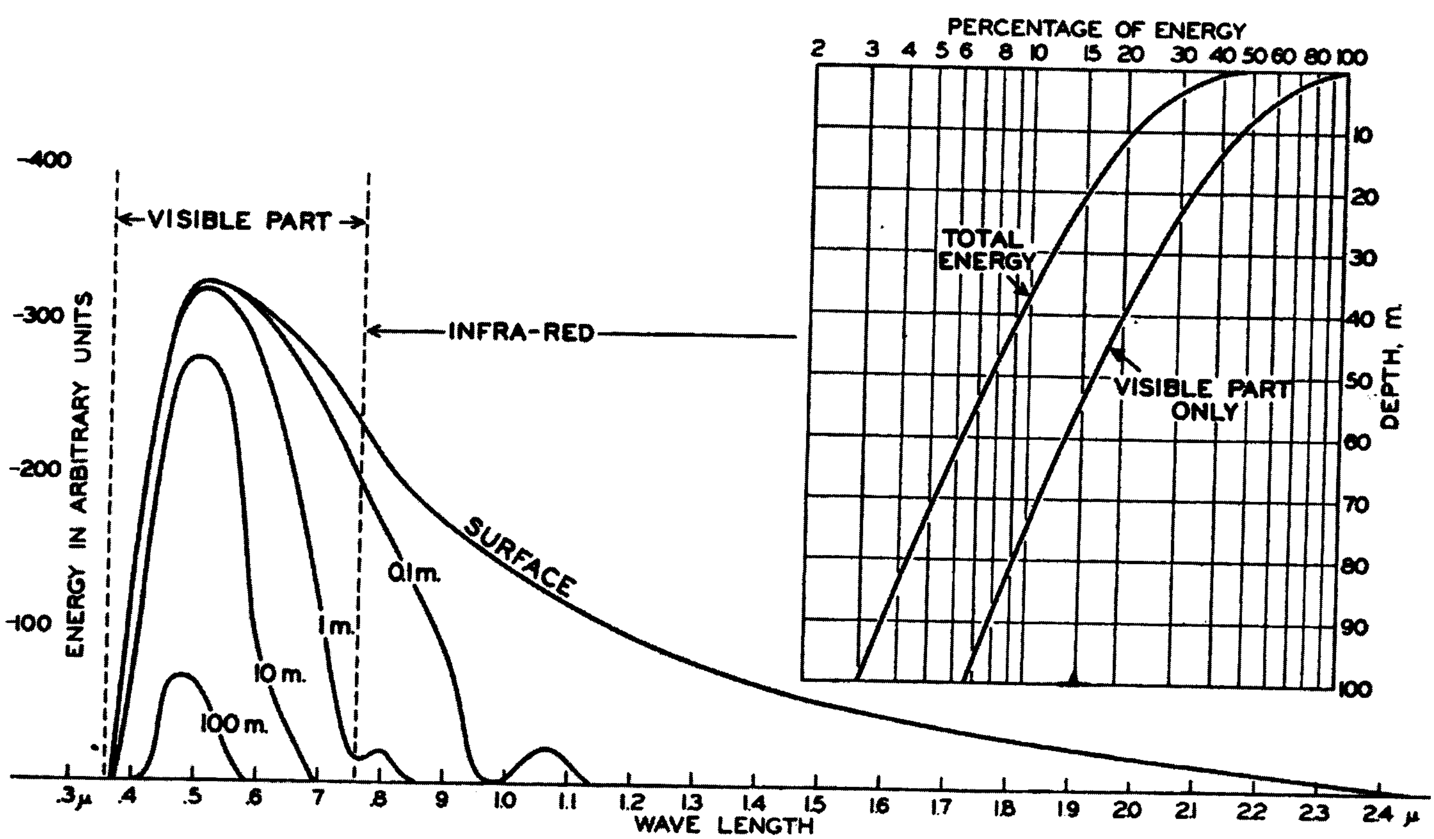


Figure 2.6 The Energy Spectrum of Incident Radiation that Penetrates a Clear Ocean to Several Depths (5)

and at the sea surface. Similarly, the spectral attenuation of incident solar radiation at the surface and various depths below the sea surface is provided by Figure 2.6. As can readily be seen, the total quantity of solar radiation (area under the curve) decreases markedly with both depth in the atmosphere and depth below the sea surface. For all practical purposes, no incident sunlight remains in the sea below a depth of approximately 100 meters under the best of water clarity conditions. In coastal and turbid waters, the loss of solar radiation is even more intense.

Both mechanical (acoustic) and electromagnetic waves are refracted when passing from one medium into a second medium with a differing density and, thus, propagation velocity. For isotropic media, Snell's law adequately describes the refraction.

Figure 2.7 depicts the refraction of an incident light ray approaching the water surface at an angle of incidence, θ_1, and refracting through the interface at refracted angle θ_2. If c_1 and c_2 are the velocities of light in air and water, respectively, then Snell's law provides

$$\frac{\sin(\theta_1)}{\sin(\theta_2)} = \frac{c_1}{c_2} = n_{21} = \frac{1}{n_{12}} \qquad [3]$$

where n_{12} is the relative index of refraction. For pure water at 15° C and a wavelength of 0.5876 microns, near the peak of the visible part of the spectrum, the index of refraction is 1.333338. The index of refraction for seawater increases with increasing salinity and decreasing temperature.

The extinction or loss of incident solar radiation with depth in the sea is the result of both absorption and scattering. Both pure water molecules, k, and suspended and dissolved material, k_w, cause absorption. Similarly, scattering is caused by water molecules, ε, and suspended and dissolved materials, ε_w. All of these components, which determine the extinction coefficient, are wavelength dependent (different for each color of light). Hence, the extinction coefficient, α, must be defined for a specific wavelength of light, λ.

$$\alpha_\lambda = k_\lambda + k_{w\lambda} + \varepsilon_\lambda + \varepsilon_{w\lambda} \qquad [4]$$

Hence, for a beam of parallel incident electromagnetic radiation with total energy intensity, I_s, at the sea surface, the corresponding intensity of total energy, I_z, at any depth z, below the surface is given by the relationship

$$I_z = I_s e^{-\bar{\alpha} z} \qquad [5]$$

where is the extinction coefficient averaged over the wavelength. And for an individual wavelength

$$(I_z)_\lambda = (I_s)_\lambda e^{-\alpha_\lambda z} \qquad [6]$$

Note that although an average extinction coefficient may be defined, representing the total energy of penetrating light in the water column, the spectral composition of light changes significantly with depth below the surface or with distance from source to receiver.

2.3.2 Ocean Acoustics

Just as in the previous case of electromagnetic propagation in the sea at optical wavelengths, Snell's law is also utilized in the case of acoustic propagation. In the acoustic case, variations in the speed of propagation are brought about by changes in both the compressibility and density of the medium. Hence, as salinity, temperature, and pressure change, either vertically or horizontally in the ocean environment, so also does the speed and direction of acoustic propagation.

The velocity of acoustic propagation, V is given by

$$V = \sqrt{\frac{M}{\rho}} \qquad [7]$$

where M is the bulk modulus of compressibility and ρ is the fluid density. In the case of the acoustic propagation in the sea, both M and ρ are functions of salinity, temperature and pressure.

The velocity of sound in water is much greater than in air, due to the much smaller compressibility of water. For typical open ocean surface seawater, at a salinity of approximately 35‰, and temperature of 30° C, the speed of acoustic propagation is 1543 m/s. Sound velocity in the sea

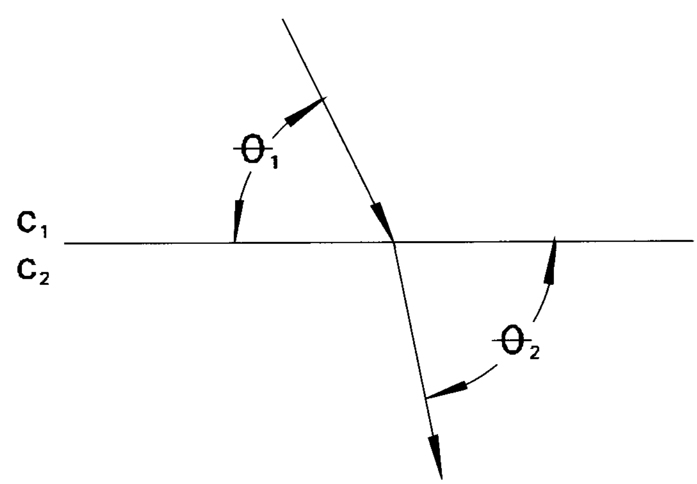


Figure 2.7 Schematic Diagram of Snell's Law

increases with increasing temperature, salinity and pressure. Within the typical ranges of these oceanic parameters, the speed of sound is dominated by the effects of changing temperature. The effect of pressure is also substantial, changing the speed of sound by about 200 m/s between the surface and deepest ocean depths. This effect must be accounted for in order to obtain accurate depth information from echo sounding.

Analogous to the optical case, acoustic energy is also absorbed and scattered by the aquatic environment. As a result of the viscosity of water, and the associated suspended and dissolved materials, a loss of kinetic energy of the propagating sound wave occurs. As kinetic energy is converted into heat, a decrease in the intensity, I, of the sound energy, proportional to the distance traveled, dx, is realized. Hence

$$I = I_0 e^{-\upsilon x} \qquad [8]$$

where I_0 is the initial intensity at $x = 0$, υ is the acoustic absorption coefficient, and x is the distance traveled from the source.

From the classical theory of Stokes and Kirchhoff the absorption coefficient for water, υ, is

$$\upsilon = \frac{16\pi^2\eta}{3\lambda^2 V\rho} \qquad [9]$$

where η is the dynamic viscosity, and λ the acoustic wavelength.

The propagation distance, d, from the source to a point where the sound intensity has been reduced to a value of 1/e or 37% of its original intensity, I_0, is given by

$$d = \frac{3\lambda^2 V\rho}{16\pi^2\eta} = \frac{3V^3\rho}{16\pi^2 n^2\eta} \qquad [10]$$

where $n = V/\eta$, the acoustic frequency.

Hence, as the frequency of the acoustic energy increases, the distance traveled to reach 37% of the original intensity decreases. If long acoustic propagation distances are desired, low frequency acoustics must be used, a technology expertly employed by whales. However, low frequency propagation is not problem free and it is advisable to use high frequencies, up to 10 000 cycles per second, for the purposes of echo sounding. As an example, at an acoustic frequency, n, of 10 000 CPS in near surface sea water at 35‰ and 10° C, the dynamic viscosity, η, is 13.9×10^{-3}, and V equals 1487 m/s, providing a propagation distance, d, of 465 km. Actual measured oceanic absorption rates tend to be much greater than this simple theory suggests. This is primarily due to the scattering of acoustic energy.

Again analogous to the optical case, variations in the speed of propagation produce a corresponding change in the direction of travel of acoustic waves. Acoustic refraction obeys Snell's law and is given by

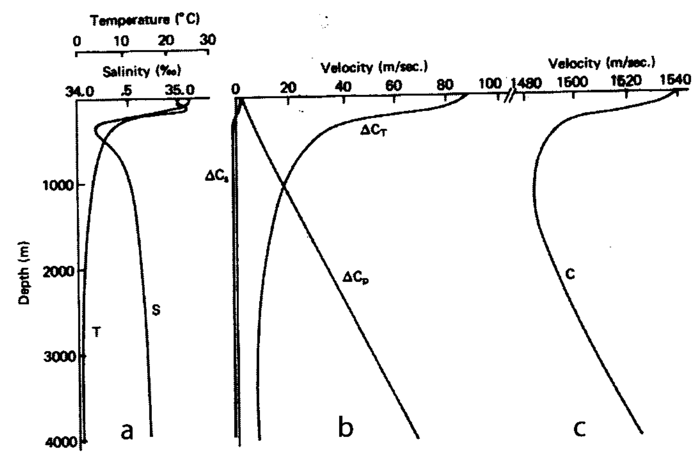


Figure 2.8 a) Typical Mid-oceanic Temperature and Salinity Profiles, b) The Correction to Speed of Sound Due to Temperature, Salinity and Pressure, c) The Resultant Speed of Sound Profile (6)

$$\frac{\sin(\theta_1)}{\sin(\theta_2)} = \frac{V_1}{V_2} \qquad [11]$$

where θ_1 and θ_2 are the incident and refracted angles in medium 1 and medium 2, respectively. Similarly, V_1 and V_2 are the sound velocities on medium 1 and 2, respectively.

Under typical ocean conditions, with a warmer surface layer overlying a colder deeper layer, acoustic energy will be refracted downward (toward the colder water region). The same principles apply to horizontal acoustic propagation through cold core eddies, with refraction of the acoustic waves toward colder water and away from warm water.

As depth increases beyond about 1000 m, temperature changes very little and pressure begins to play an important role in the determination of the speed of sound. This results in the potential for the velocity of sound to increase with depth beyond this point. As this occurs, the sound waves may refract back up towards the water surface. Figure 2.8 shows typical temperature and salinity profiles for a Pacific Ocean site. The center panel shows the corrections to the speed of sound due to temperature, salinity and pressure, and the third panel shows the speed of sound profile exhibiting a minimum at about 500 m of depth.

The combined effects of downward refraction above and upward refraction below result in the potential for sound waves to be trapped in a "channel" and transmitted over very long ranges. This "channel" is referred to as the SOFAR (sound fixing and ranging) channel. It permits long-range detection of submarines and other underwater devices designed for search and rescue.

2.4 OCEAN CURRENTS AND CIRCULATION

When the wind blows across the water surface, approximately 97% of the momentum that is transferred from the wind into the fluid goes into generating the large-scale circulation ofthe body of fluid (currents). This leaves only 3% of the momentum from the wind for the generation of surface wave fields. On human standards, this mere 3% results in an enormous manifestation of energy capable of sinking ships, destroying harbors, and transporting huge quantities of sediment along the shorelines. We will first consider the generation of ocean and large lake circulation. The following section will consider surface wave motions.

2.4.1 Air/Water Interface

The longer the wind blows across the water surface, the greater the depth of penetration of the current into the body of water. As can be seen schematically in Figure 2.9, the surface waters respond relatively quickly to the shear stress imparted across the air-sea interface by the motion of the wind. The approximate rule of thumb is that the upper few centimeters of fluid move at approximately 2% of the wind speed. Hence, a 10 m/s (20-knot) wind blowing across the water surface will produce a current in the general direction of the wind of approximately 20 cm/s in magnitude.

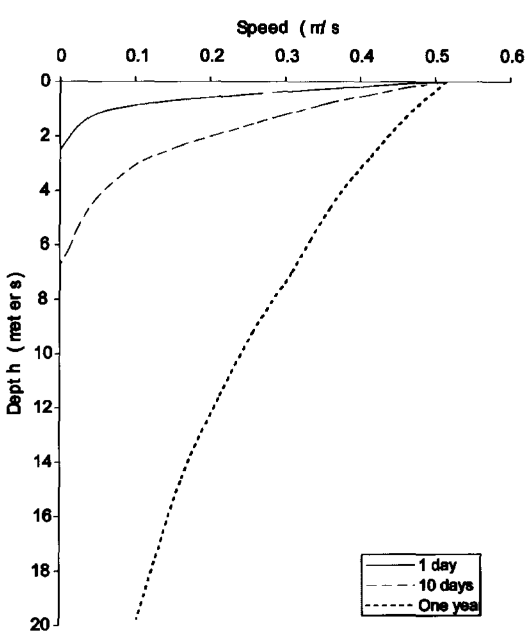


Figure 2.9 Current Velocity Profile with Depth for Wind of Three Duration Periods

It should be noted that (wer long time periods or large spatial distances, the effects of the earth's rotation must also be considered.

Objects floating at the water surface with significant windage (protrusion above the water surface), such as a human in a life vest, wreckage, or debris, generally move with a greater percentage of the wind. Approximately 3% of the wind speed is commonly used.

For material moving with the water fluid, such as contaminants, spills, or oil at the water surface, generally 2.0-2.5% of the wind speed is the accepted value for estimating motion. Since wind speed and direction often changes over open wll;ter, the correct prediction of surface motion is the vector combination of l()()% of the current, plus 2-3% of the wind.

Momentum from the wind, which is imparted to the flpid surface, is transferred vertically downward into the fluid body primarily by turbulent motions of the fluid itself. Although the surface magnitude of the flow (upper few cm) will remain constant for a given wind speed, the velocity of the underlying flow will continue to increase until a steady state is obtained. In reality, this steady state is never actually attained in the ocean, and is relatively rare in large bodies of water. Hence both the oceans and inland seas are in a constant state of readjustment to varying wind conditions on a global scale.

Since ocean and large inland sea circulation occurs over relatively large spatial scales, the effect of the earth's rotation is a major factor in controlling the direction of ocean currents. Hence, when we examine the equations of motion for ocean circulation, these equations will reflect sources and sinks of momentum, (primarily occurring at the boundaries, surface, edges and bottom), terms which reflect the transport of momentum due to turbulent motions, and the effects of the earth's rotation or coriolis force.

2.4.2 Equations of Motion

The equations, which describe oceanic motions, originate from the application of Newton's second law relating force, mass and acceleration

$$\overline{F} = M\overline{A} \qquad [12]$$

Since, in the ocean environment, variations in the field of mass are extremely important, and the forces acting on the fluid can be numerous, it is more convenient to express Newton's law as

$$\sum \bar{F} = \frac{d}{dt} M\bar{V} \qquad [13]$$

or the sum of the forces equals the time rate of change of momentum. The most general three-dimensional form of this equation, incorporating viscous effects, is known as the Navier-Stokes equations for a compressible fluid on a non-rotating earth and is given by Lamb (6) as

$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} + w\frac{\partial u}{\partial z} = -\frac{1}{\rho}\frac{\partial p}{\partial x} + \frac{1}{3}\left[\frac{\mu}{\rho}\left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 v}{\partial y \partial x} + \frac{\partial^2 w}{\partial z \partial x}\right)\right] + \frac{\mu}{\rho}\nabla^2 u \qquad [14]$$

$$\frac{\partial v}{\partial t} + u\frac{\partial v}{\partial x} + v\frac{\partial v}{\partial y} + w\frac{\partial v}{\partial z} = -\frac{1}{\rho}\frac{\partial p}{\partial y} + \frac{1}{3}\left[\frac{\mu}{\rho}\left(\frac{\partial^2 u}{\partial x \partial y} + \frac{\partial^2 v}{\partial y^2} + \frac{\partial^2 w}{\partial z \partial y}\right)\right] + \frac{\mu}{\rho}\nabla^2 v \qquad [15]$$

$$\frac{\partial w}{\partial t} + u\frac{\partial w}{\partial x} + v\frac{\partial w}{\partial y} + w\frac{\partial w}{\partial z} = -\frac{1}{\rho}\frac{\partial p}{\partial z} - g + \frac{1}{3}\left[\frac{\mu}{\rho}\left(\frac{\partial^2 u}{\partial x \partial z} + \frac{\partial^2 v}{\partial y \partial z} + \frac{\partial^2 w}{\partial z^2}\right)\right] + \frac{\mu}{\rho}\nabla^2 w \qquad [16]$$

$$\frac{\partial(\rho u)}{\partial x} + \frac{\partial(\rho v)}{\partial y} + \frac{\partial(\rho w)}{\partial z} = -\frac{\partial \rho}{\partial t} \qquad [17]$$

where

$$\nabla^2 = \frac{\partial}{\partial x^2} + \frac{\partial}{\partial y^2} + \frac{\partial}{\partial z^2} \qquad [18]$$

μ is the fluid viscosity, u, v, and w are the velocity components in the x, y and z directions, respectively, p is the pressure, g, gravity and ρ the fluid density.

The earth is an oblate spheroid, with the equatorial radius exceeding the polar radius, rotating on its axis in a counter-clockwise fashion when viewed from above the North Pole. The rotation rate is 1 revolution in approximately 24 hours, or an angular rotation rate, ω, of 7.29×10^{-5} sec^{-1}. When viewed from space, this results, at the equatorial radius, in a transverse, or easterly velocity of all particles (solid earth, fluid earth, and atmosphere near the earth's surface) of approximately 1600 km per hr.

Moving poleward from the equator, the radius to the earth's surface from the axis of rotation decreases. Correspondingly, the transverse velocity also decreases, approaching zero at both poles. Figure 2.10 shows that the transverse velocity of all particles are approximately 1400 kmIhr at 30 degrees north and south latitude, and 800 km/hr at 60 degrees north and south latitude. A simple and useful way to view the effect of the earth's rotation on fluid particles (ocean and atmosphere) is to visualize an object (particle of water, moving ship, moving aircraft) traversing the earth's surface from the equator to the North Pole. As the object moves from the equator, with a transverse velocity of 1600 kmIhr, to 30 degrees north latitude, it is encountering a region where all particles are in equilibrium with the earth's rotation at a speed of 1400 kmIhr. Hence, our moving particle (mass of water, ship, or aircraft) will possess a transverse velocity greater than those particles in the region into which it is moving. As viewed from space it will appear to move ahead of those particles at 30 degrees north latitude, or experience a deflection to the *right* of its velocity. Similarly, if we were to continue our journey poleward: approaching particles at greater latitudes, deflection would again be to the right of the particles at the new location. It can be readily seen that the rate of decrease of transverse velocity increases with latitude and hence, the intensity of the Coriolis deflection to the right, also increases with latitude.

Including the effects of the earth's rotation (Coriolis force), the Navier-Stokes equations become

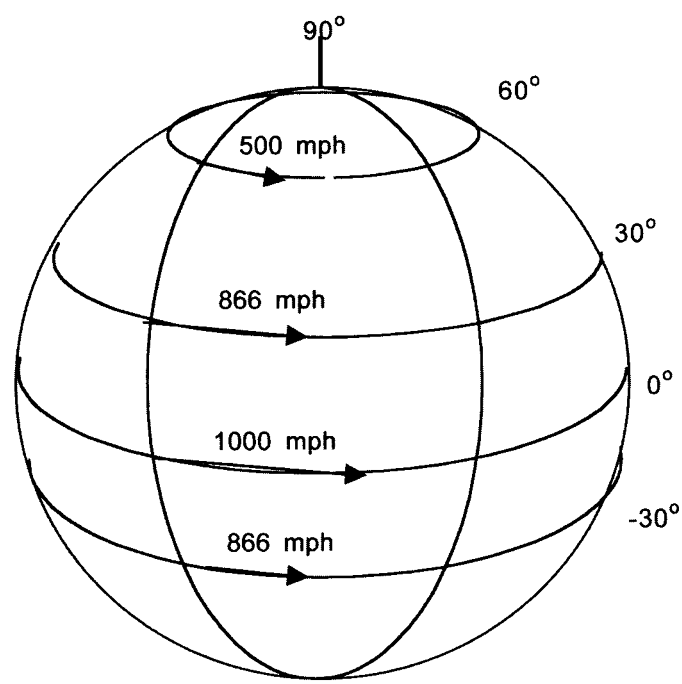


Figure 2.10 Variation in Tangential Velocities of Particles at Rest on the Earth's Surface with Latitude

$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} + w\frac{\partial u}{\partial z} -2\omega(\sin\phi v - \cos\phi w) = -\frac{1}{\rho}\frac{\partial p}{\partial x} + F(x) + D(x) \qquad [19]$$

$$\frac{\partial v}{\partial t} + u\frac{\partial v}{\partial x} + v\frac{\partial v}{\partial y} + w\frac{\partial v}{\partial z} + 2\omega \sin\phi u = -\frac{1}{\rho}\frac{\partial p}{\partial y} + F(y) + D(y) \qquad [20]$$

$$\frac{\partial w}{\partial t} + u\frac{\partial w}{\partial x} + v\frac{\partial w}{\partial y} + w\frac{\partial w}{\partial z} - 2\omega \cos\phi u = -\frac{1}{\rho}\frac{\partial p}{\partial z} - g + F(z) + D(z) \qquad [21]$$

$$\frac{\partial(\rho u)}{\partial x} + \frac{\partial(\rho v)}{\partial y} + \frac{\partial(\rho w)}{\partial z} = -\frac{\partial \rho}{\partial t} \qquad [22]$$

where the terms on the right hand side, F(x) and D(x), represent the external forces and dissipative forces, respectively, ω is the rotation rate of the earth, 7.29×10^{-5} sec^{-1} and ϕ is the latitude.

2.4.3 Atmospheric Circulation

The circulation in the atmosphere is controlled by a balance of the earth's rotation and thermodynamic forcing. The strength of the wind on our planet is controlled by the corresponding strength of the equator to pole temperature difference. Through geologic history, when the equator to pole temperature variance was greater, so too were the winds. Figure 2.11 provides a representation of the general circulation of the atmosphere.

Atmospheric circulation is driven by intense solar heating in the equatorial regions, balanced by a corresponding deficit of heat in the Polar Regions. The resulting surplus of heat in equatorial to mid latitude regions and a deficit of incident solar radiation in mid-latitudes to Polar Regions require a redistribution of heat on a global scale. Hence, Polar Regions receive less than the amount of heat required to maintain the heat budget and lower latitudes receive more heat than that required to maintain the heat budget. A balance between the required amount of incoming solar radiation, to maintain the earth's heat budget and that re-radiated back to space, is achieved at approximately 38 degrees north and south latitude. Hence, enormous equatorial to polar heat transfers must occur to maintain the overall global heat balance of the planet. Atmospheric winds and oceanic currents are responsible for maintaining this heat balance.

In equatorial regions, as intense solar radiation supplies heat to the earth surface (most of which is covered by water), heat is transported from the earth's surface to warm the lower regions of the atmosphere. Additionally, water vapor is evaporated from the earth's surface, and also supplied to the lower atmosphere (a sea to air transfer of mass).'Since heating is more intense in equatorial regions, the air masses directly above the equatorial regions of the earth become heated and buoyant relative to the air masses at higher latitudes. Hence, these air masses begin to rise relative to their surroundings. Since these air masses are heavily laden with water vapor, the rising air masses eventually cool and initiate the condensation of water vapor into the formation of intense clouds and precipitation. The subsequent release of latent heat, in the form of the phase change from water vapor to liquid water, provides a secondary heating mechanism to the equatorial atmosphere. Since gravity prevents the rising air mass from escaping from the planet, these rising air masses spread in the upper atmosphere towards both the north and south poles.

Once in the upper regions of the atmosphere, (Figure 2.11, point A and *1\)*, intense radiative cooling occurs in the atmosphere. This poleward bound air mass becomes dense relative to its surroundings, and sinks toward the earth's surface while continuing its journey. Since the air mass is now almost totally devoid of moisture, it is a very clear, dry air mass descending toward the earth's surface, creating the high-pressure regions associated with the mid-latitude deserts of the world. Continuing its journey poleward (Figure 2.11, point Band B'), once again in contact with the

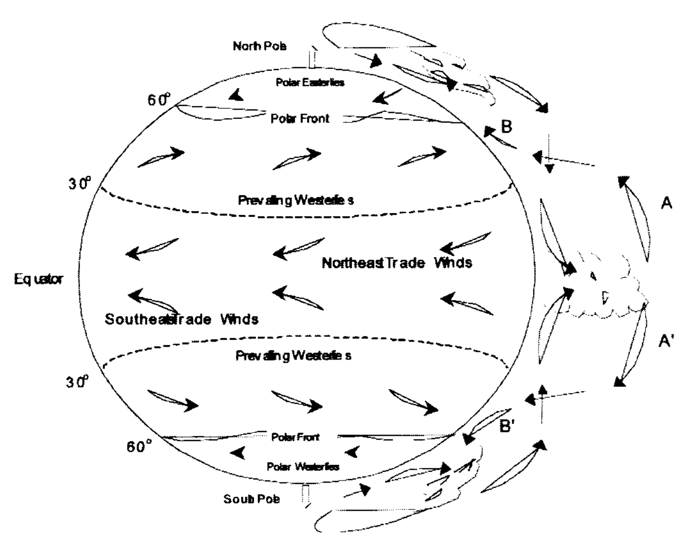


Figure 2.11 General Circulation of the Atmosphere

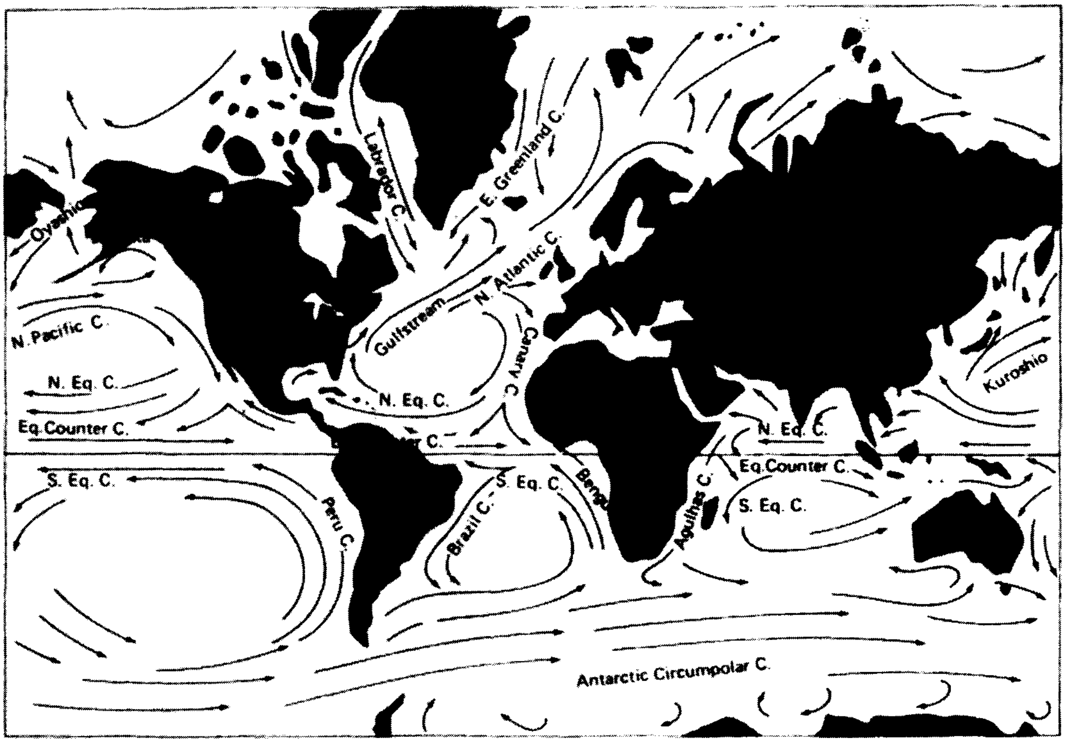


Figure 2.12 Major Surface Currents of the Ocean

earth's surface (again most of which is water), the air mass receives both heat and moisture fluxes from the earth's surface. These fluxes induce a buoyant air mass, rising at approximately 60 degrees north and south latitude. Just as at equatorial regions, this rising air mass stimulates the airborne phase change from water vapor to liquid water, producing intense cloud cover and precipitation along the region of the polar front. Continuing its journey poleward, the air mass once again sinks in polar regions and returns southward now along the earth's surface rising again at 60 degrees north and south latitudes, cooling in space, and descending, thus completing the cycle at 30 degrees north and south latitude. Hence, the mass of the atmosphere is conserved, and this thermodynamically driven circulation results in winds along the earth's surface flowing north and south, in the absence of the earth's rotation.

With the addition of the effects of the earth's rotation, these north and south flowing winds are imparted with an east-west component. With rotation induced Coriolis deflection, to the right in the Northern Hemisphere and to the left in the Southern Hemisphere, the prevailing surface wind patterns are derived. Between the equator and approximately 30 degrees north and south latitude, the trade wind easterlies reside (winds blowing from east to west). Between 30 and 60 degrees north and south latitude the prevailing westerlies exist. In high latitudes, the polar easterlies dominate. Comparison of this general atmospheric circulation pattern to the ocean surface circulation (Figure 2.12) provides a striking similarity between force and response.

2.4.4 Geostrophic Flow

The simplest theoretical form of ocean motion is referred to as geostrophic flow. Geostrophic flow is the balance between the Coriolis and pressure gradient forces, all other forces being negligible. It is a steady horizontal flow (no variation with time) and closely accounts for the flow within the interior of the ocean, away from surface, edge and bottom boundaries and their associated effects. Hence, this simple flow accounts for approximately 98% of the ocean volume.

The governing equations for this flow are:

$$2\omega \sin\phi v = \frac{1}{\rho}\frac{\partial p}{\partial x} \qquad [23]$$

$$2\omega \sin\phi u = -\frac{1}{\rho}\frac{\partial p}{\partial y} \qquad [24]$$

$$2\omega \cos\phi u = \frac{1}{\rho}\frac{\partial p}{\partial z} + g \qquad [25]$$

$$\frac{\partial(\rho u)}{\partial x} + \frac{\partial(\rho v)}{\partial y} = 0 \qquad [26]$$

The geostrophic balance of forces for the Northern Hemisphere is as depicted in Figure 2.13. The pressure gradient is directly opposed by the Coriolis force, which is to the right of the velocity. In this situation, the current flows parallel to the isobars (or lines of constant pressure) with high pressure to the right in the Northern Hemisphere. The geostrophic balance in the Southern Hemisphere would again have Coriolis force and pressure gradient opposed (equal and opposite), with the Coriolis force directed to the left of the velocity. Thus, in the Southern Hemisphere, the current again flows parallel to the isobars, however, high pressure is located to the left.

In the interior of the ocean, away from the surface, edge and bottom boundaries, the resultant horizontal circulation is a large gyre continually turning to the right, or clockwise in the Northern Hemisphere and a corresponding left turning or counter-clockwise gyre, in the Southern Hemisphere Ocean. Figure 2.12 provides a schematic of general ocean circulation demonstrating this effect.

2.4.5 Ekman Flow and Vertical Current Structure

The deflection of ocean surface currents relative to the wind was first observed by Fridtjof Nansen in the late 1800s. Nansen allowed his wooden oceanographic sailing research vessel, *FRAM,* to freeze into the Arctic pack ice (Norwegian North Polar Expedition, 1893-96), and recorded its drift, relative to the wind, for a period of approximately two years until the ship could be freed. His observations were placed in theory by Ekman (8), resulting in the classic treatise on oceanic wind-driven circulation. In this theoretical flow field, a uniform wind stress at the sea surface drives a flow in an unbounded ocean. This flow is subject to Coriolis and frictional influences only.

The most striking feature of this theory is that the wind induced, surface current direction is 45 degrees to the right of the wind direction in the Northern Hemisphere (to the left in the Southern Hemisphere). Ekman's theory also suggests that once the surface layer of the ocean is placed in motion by the frictional coupling of the wind above the water, each successive layer below will be affected through vertical turbulent mixing. There will be a corresponding decrease in velocity, as well as a turning to the right in the Northern Hemisphere and to the left in the Southern Hemisphere with depth. The resultant current structure is depicted in Figure 2.14. The velocity decreases exponentially with depth to the depth of frictional influence (the depth to which the constant wind can effectively place the ocean in motion).

As a result of the constant turning of current direction to the right (in the Northern Hemisphere) the direction of flow at the bottom of the Ekman surface layer is 180 degrees from that of the surface current, or 235 (45 + 180) degrees from the wind.

Vertically integrating this flow over the region from the depth of frictional influence to the surface, produces net flow 90 degrees to the right of the wind. Hence, passive contaminants mixed in this upper region of the ocean will be transported at right angles to the prevailing wind direction (to the right in the Northern Hemisphere and to the left in the Southern Hemisphere).

Below the depth of frictional influence, and hence below the reach of the surface layer (typically at a depth corresponding to the base of the thermocline, approximately

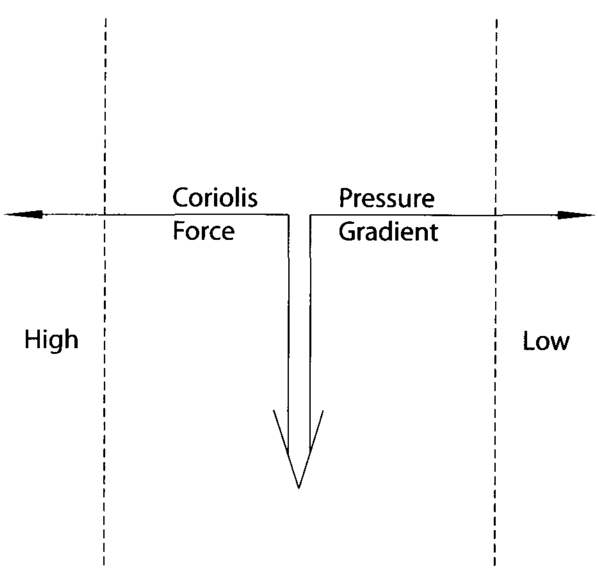


Figure 2.13 The Geostrophic Balance of Forces for the Northern Hemisphere

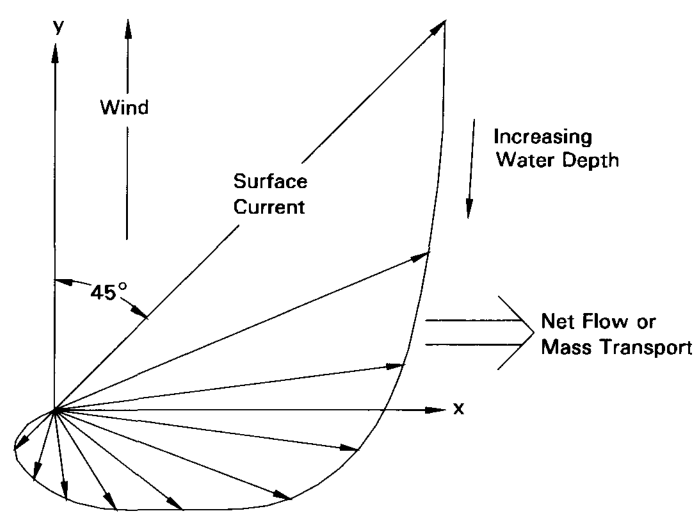


Figure 2.14 A Projection of the Vertical Wind Driven Surface Current Structure on a Horizontal Plane (8)

100-200 m), the flow is generally geostrophic. This mid-depth region of geostrophic flow extends vertically downward through the bulk of the interior of the ocean until again reaching a region of frictional influence near the bottom boundary. Just as in the case of the surface layer, an Ekman bottom boundary layer is also formed. The bottom layer is driven from above by the geostrophic flow of the interior of the ocean and is modified by both the increasing frictional influence of the approaching bottom and the earth's rotation. This combination of forces again results in turning toward the pressure gradient, as friction is increased (approaching the bottom boundary) and decreasing magnitude of the current. A schematic view of the bottom layer is depicted by Figure 2.15.

Combining these three components of oceanic flow, a bottom layer, a mid-depth interior region dominated by geostrophic flow, and a surface layer, results in Ekman's elementary current system (Figure 2.16). This relatively simple flow, being driven by the wind and balanced by pressure gradient forces and frictional forces represents the basis of horizontal ocean circulation. It should be noted, as the diagram depicts, that the current experienced at the surface is the vector addition of the underlying geostrophic flow and the Ekman surface layer circulation at each particular level.

As an example, along an infinite straight Northern Hemisphere coastline, as depicted in Figure 2.17, with the wind blowing parallel to shore (from right to left) and (a) is the pure drift current at the surface, (b) is the actual surface current, (c) is the geostrophic current, and (d) is the bottom current, the resulting net mass transport in the surface layer results in a transport of fluid onshore. This produces an offshore pressure gradient resulting in a mid-depth, geostrophic flow also parallel to the coast (from right to left). In this example, the bottom current vvould be offshore and down coast.

With this mid-depth g~ostrophic flow moving dOwn coast, and a net mean bottom transport offshore and down coast, objects placed at the surface of this flow would tend to move onshore and downcoast, contaminants floating with the mid-depth water would be transported shore parallel and similarly, objects near the bottom would be transported offshore. The opposite would be true in the Southern Hemisphere.

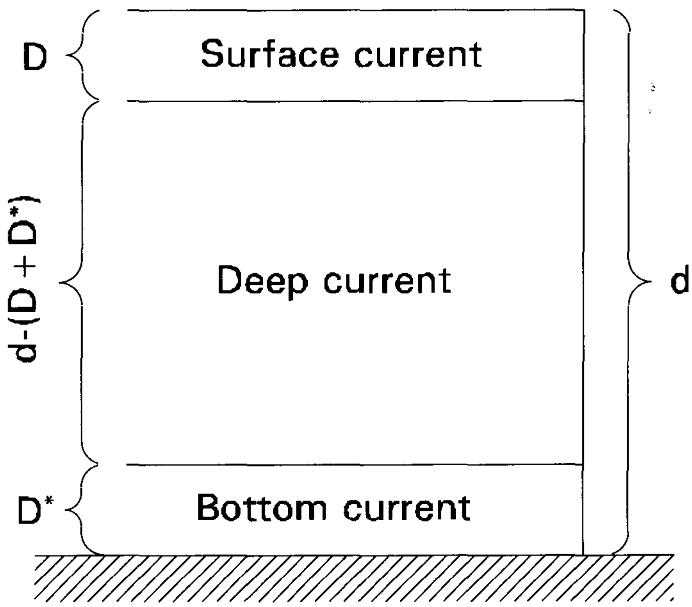


Figure 2.16 Vertical Distribution of Ekman's Elementary Current System

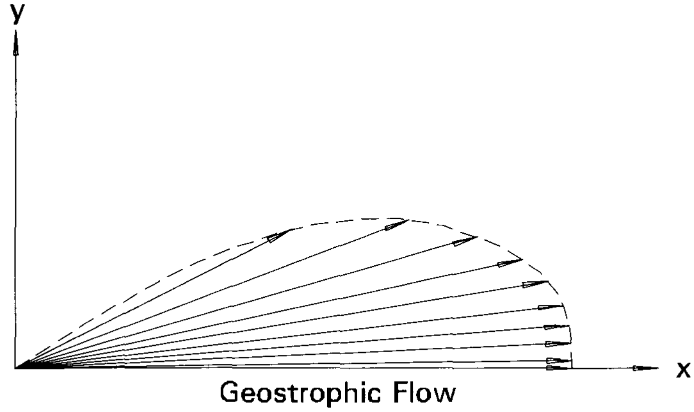


Figure 2.15 A Projection of the Vertical Current Structure on the Sea Bottom on a Horizontal Plane (8)

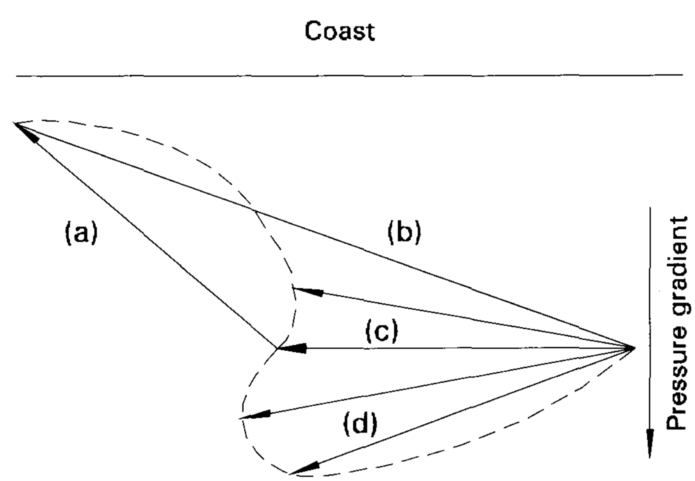


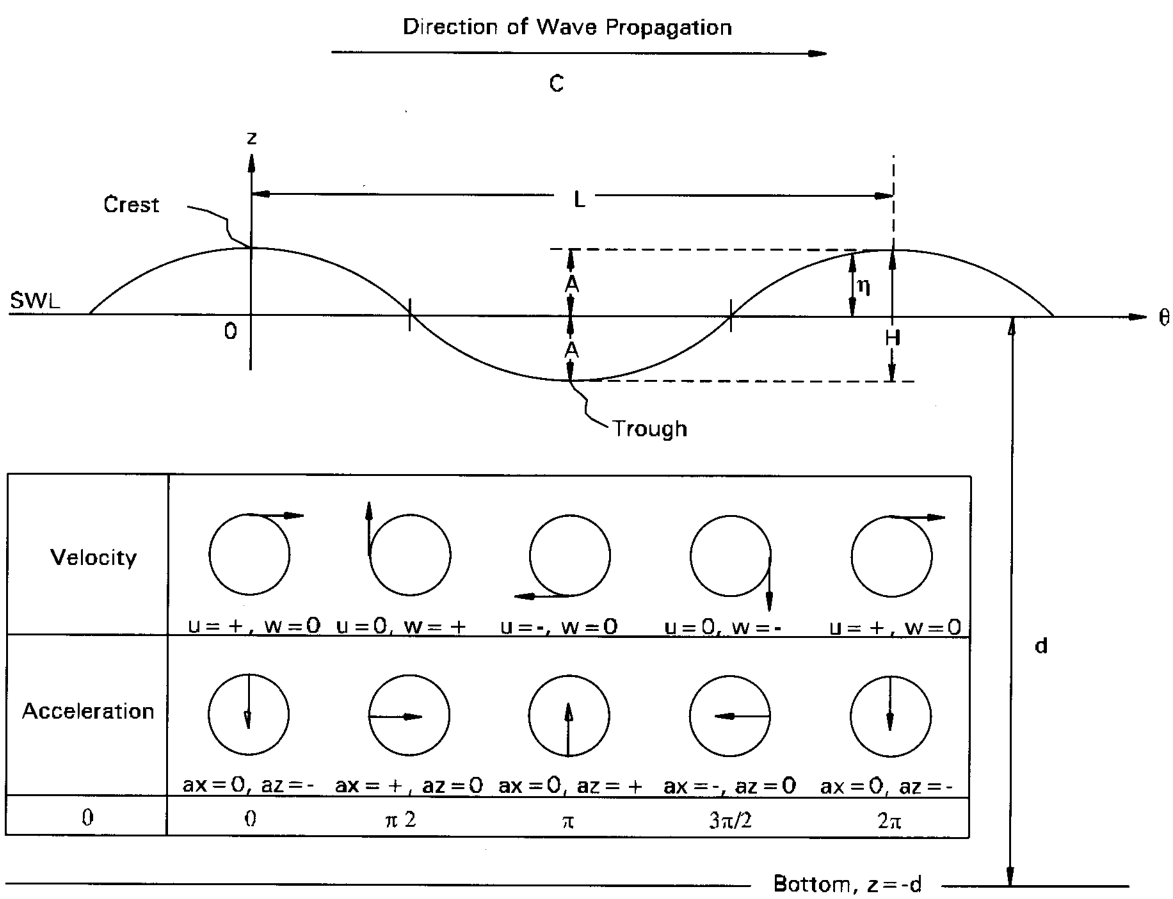
Figure 2.17 Vector Diagram of Ekman's Elementary System

2.4.6 Upwelling, Downwelling, and Seiche

One additional class of wind-induced motion is worthy of consideration. As the wind blows across the water surface, water is transported in the general direction of the wind. This produces a *piling* of water along the downwind shoreline and a depression in the thermocline (region of rapidly decreasing temperature). To conserve fluid mass, a general offshore flow along the bottom boundary is created. Correspondingly, on the upwind side of the basin, subjected to the strong influence of the wind, one would expect to have onshore flow along the bottom, offshore flow at the surface, and an elevation of the thermocline, or the accumulation of cold water near the coastal region. Hence, the upwind coast is referred to as an upwelling coast, and the downwind coast as a downwelling coast.

This phenomenon also exists on oceanic scales when the wind blows parallel to a coast producing a mass transport of water perpendicular to shore. If the water is transported offshore, an upwelling occurs bringing nutrient'rich deep water into the photic zone and enhancing biological productivity.

In the case of a wind event over an enclosed basin, when the wind weakens, the water, which has been forced to' one end of the basin, is released and the basin effectively sloshes back and forth at its natural period of oscillation. This phenomenon is referred to as a seiche. As an example, Lake Erie located in the temperate region of North America, which is relatively shallow in mean depth and has its long axis oriented into the prevailing westerlies, is noted for experiencing great seiches. The longitudinal seiche period (natural period of oscillation) of Lake Erie is approximately 14.2 hours. The maximum water level elevation difference, recorded between Buffalo, New York on the east end of the basin and Toledo, Ohio on the west end of the basin. of some 5 m occurred during a December storm.



$\eta = A \cos(kx - \sigma t)$

$\eta = A = H/2$ at wave crest

$\eta = -A = -H/2$ at wave trough

Figure 2.18 A Sinusoidal Surface Wave Propagating in the Positive x Direction with Underlying Particle Velocities and Acceleration Shown

2.5 WAVE MECHANICS

As the wind blows across the sea surface, large lake or bay, momentum is imparted from the wind to the sea surface. As previously discussed, approximately 97% of this momentum is used to generate the general circulation (currents) of the water body and the remainder supplies the development of the surface wave field. Although this surface wave momentum represents a small percentage of the total momentum, it results in an enormous quantity of energy on human scales.

Waves on the free surface of a body of water are the combined result of a disturbing force (that which is responsible for the creation of the deformation), and a restoring force (which attempts to restore the surface back to equilibrium). Surface waves are generally characterized by their height, length, period and by the total water depth in which they are traveling. A two-dimensional sketch of a sinusoidal surface wave propagating in the x-direction can be seen in Figure 2.18. The wave height, H, is the vertical distance between the crest and trough of the wave. The wavelength, L, is the horizontal distance between any two corresponding points on successive waves and the wave period, T, is the time required for the passage between two successive crests or troughs. The equilibrium'position used to reference surface wave motion, still water level (SWL), is at z = 0 and the bottom is located at z = -<1, where d is the local water depth. The celerity of a wave, C, is the speed of propagation of the wave form (phase speed), defined as C=L/T.

Most ocean waves are progressive, which implies that their wave form travels at celerity, C, relative to a background. In contrast, standing waves, whose wave form remains stationary relative to a background, occur in the simplest case from the interaction of two progressive waves traveling in opposite directions and are often observed near reflective barriers. Progressive, deep ocean waves are oscillatory, meaning that the water particles making up the wave do not exhibit a net motion in the direction of wave propagation. However, as waves enter shallow water, they begin to exhibit a net displacement of water in the direction of wave propagation and are classified as translational.

2.5.1 Linear Wave Theory

The free surface water elevation, 11, for a real water wave propagating over an irregular, permeable bottom is quite complex. However, by employing several simplifying assumptions, the mathematical problem becomes much more tenable. In general, viscous effects are assumed negligible (concentrated near the bottom), the flow is assumed irrotational and incompressible, and the wave heights are assumed small compared to wavelength. Given this set of assumptions, a remarkably simple solution can be obtained for the surface wave boundary value problem.

This simplification, which is referred to as linear, small-amplitude wave theory, is remarkably accurate and is the standard for many naval architecture, ocean and coastal engineering applications. Furthermore, the linear nature of this formulation allows for the free surface to be represented by the superposition of sinusoids of different amplitudes and frequencies, which facilitates the application of Fourier decomposition and associated spectral analysis techniques. Hence, we will now concentrate on characteristics of linear, progressive, small-amplitude waves.

The equation for the free surface displacement of a progressive wave is given by

$$\eta = A\,cos(kx - \sigma t) \qquad [27]$$

where the wave amplitude, $A = H/2$, the wave number, $k = 2\pi/L$, and wave frequency $\sigma = 2\pi/T$. The dispersion relation, which relates individual wave properties and local water depth, d, to wave propagation behavior is given by

$$\sigma^2 = gk\,tanh(kd) \qquad [28]$$

where g is the acceleration of gravity.

From equation 28 and the definition of wave celerity C, it can be shown that the wave propagation speed as a function of local water depth is given by

$$C = \frac{\sigma}{k} = \frac{gT}{2\pi}\,tanh(kd) \qquad [29]$$

and similarly, the wave length by

$$L = \frac{gT^2}{2\pi}\,tanh(kd) \qquad [30]$$

The hyperbolic function approaches useful simplifying limits for both large values of kd (deep water) and for small values of kd (shallow water). Applying these limits to 29 and 30 results in expressions for deep water ($\tanh(kd) \approx 1$) of:

$$C_0 = \frac{gT}{2\pi} \qquad [31]$$

and

$$L_0 = \frac{gT^2}{2\pi} \qquad [32]$$

where the subscript, 0, denotes deep water.

A similar application for shallow water, where tanh (kd) ≈ kd, results in

$$C = \sqrt{gd} \qquad [33]$$

Hence, wave phase speed in shallow water is dependent only on the water depth with all wavelength waves traveling at the same speed. This phenomenon is known as non-dispersive.

The normal limits for deep and shallow water, respectively, are kd > π and kd < π/10 (d/L > 1/2 and d/L < 1/20). Although modifications of these limits are used in practice for specific applications, the region between these two limits (π/10 < kd < π) is defined as intermediate depth water and requires use of the full equations 29 and 30.

A useful relation for calculating wave properties at any water depth based upon knowledge of deep water wave properties, is:

$$\frac{C}{C_0} = \frac{L}{L_0} = tanh\left(\frac{2\pi d}{L}\right) \qquad [34]$$

Values of d/L can be calculated as a function of d/L_0 by successive approximations using

$$\frac{d}{L} tanh\left(\frac{2\pi d}{L}\right) = \frac{d}{L_0} \qquad [35]$$

Wiegel (9) has tabulated values of d/L as a function of d/L_0 as does Appendix C of the Shore Protection Manual (10) along with many other useful functions of d/L.

2.5.1.1 Particle motions and accelerations

The horizontal component of particle velocity beneath a linear, progressive wave is given by

$$u = \frac{H}{2}\sigma\frac{cosh\big(k(d+z)\big)}{sinh(kd)}cos(kx - \sigma t) \qquad [36]$$

Similarly, the vertical particle velocity is given by

$$w = \frac{H}{2}\sigma\frac{sinh\big(k(d+z)\big)}{sinh(kd)}sin(kx - \sigma t) \qquad [37]$$

The corresponding horizontal and vertical particle accelerations are, respectively

$$a_x = \frac{\partial u}{\partial t} = \frac{H}{2}\sigma^2\frac{cosh\big(k(d+z)\big)}{sinh(kd)}sin(kx - \sigma t) \quad [38]$$

and

$$a_x = \frac{\partial w}{\partial t} = -\frac{H}{2}\sigma^2\frac{sinh\big(k(d+z)\big)}{sinh(kd)}cos(kx - \sigma t) \quad [39]$$

It can be seen from equations 36 and 37 that the horizontal and vertical particle velocities are 90° out of phase at any position along the wave profile. Extreme values of horizontal velocity occur in the crest (+, in the direction of wave propagation) and trough (-, in the direction opposite to the direction of wave propagation) while extreme vertical velocities occur mid-way between the crest and trough, where water displacement is zero. The u and w velocity components are minimized at the bottom and increase with distance upward in the water column. Maximum vertical accelerations correspond to maximum horizontal velocities and maximum horizontal accelerations correspond to maximum vertical velocities. Figure 2.18 also provides a graphic summary of these relationships.

The particle displacements within a progressive wave are obtained by integrating the velocity with respect to time and are simplified by using the dispersion relation 28 to give a horizontal displacement

$$\xi = -\frac{H}{2}\frac{cosh\big(k(d+z_0)\big)}{sinh(kd)}sin(kx_0 - \sigma t) \qquad [40]$$

and vertical displacement

$$\zeta = \frac{H}{2}\frac{sinh\big(k(d+z_0)\big)}{sinh(kd)}cos(kx_0 - \sigma t) \qquad [41]$$

In the previous equations, the coordinates (x_0, z_0) represent the mean position of an individual particle. It can be shown by squaring and adding the horizontal and vertical displacements that the general form of a water particle trajectory beneath a linear, progressive wave is elliptical. In deep water, particle paths are circular and in shallow-water they are highly elliptical as shown in Figure 2.19.

2.5.1.2 Pressure field

The pressure distribution beneath a progressive water wave is given by the following form of the Bernoulli equation

$$p = -\rho g z + \rho g \eta K_p(z) \qquad [42]$$

where p is fluid density and K_p, the pressure response coefficient, given by

$$K_p = \frac{cosh\big(k(d+z)\big)}{cosh(kd)} \qquad [43]$$

which is always less than 1, below mean still water level. The first term in equation 42 is the hydrostatic pressure term and the second is the dynamic pressure term. The dynamic pressure term accounts for two factors that influence pres-

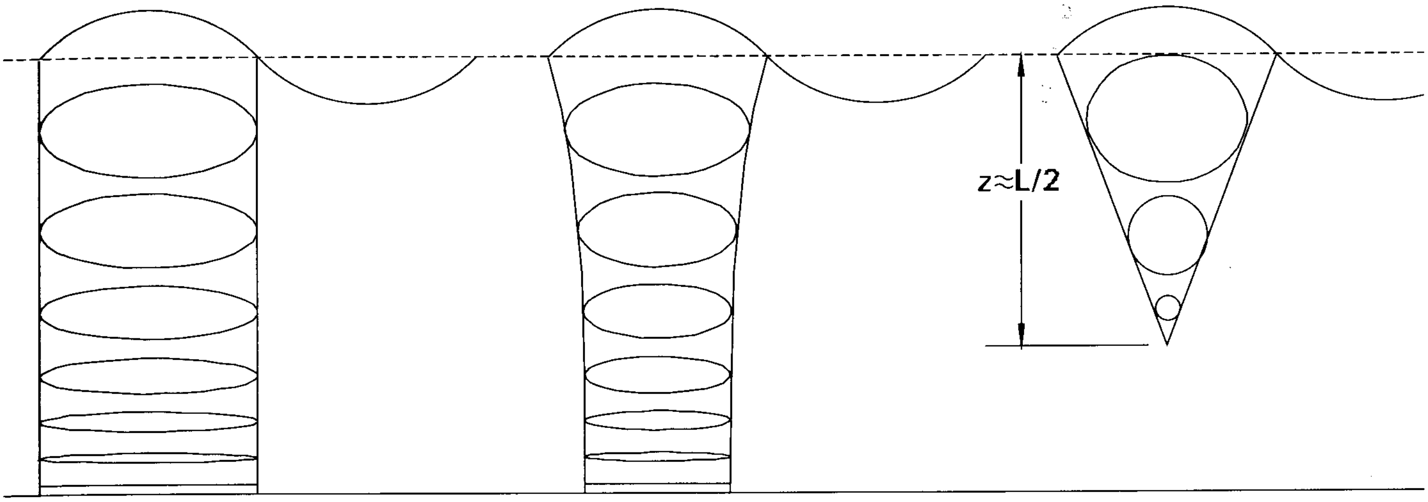


Figure 2.19 Particle Trajectories Beneath a Deep, Intermediate, and Shallow Water Wave

sure, the free surface displacement, η, and the vertical component of acceleration.

A frequently used method for measuring waves is to record pressure fluctuations from a bottom-mounted or relatively deeply moored pressure gauge. Isolating the dynamic pressure (P_D) from the recorded signal by subtracting out the hydrostatic pressure gives the relative free surface displacement

$$\eta = \frac{P_D}{\rho g K_p(-d)} \quad [44]$$

where K_p (-d) = l/cosh(kd). It is necessary, therefore, when determining wave height from pressure records to apply the dispersion relationship equation 28 to obtain K_p from the frequency of the measured waves. It is important to note that K_p, for short period waves, is very small at the bottom (-d), which means that very short period waves may not be measured by a pressure gauge. A summary of the formulations for calculating linear wave theory wave characteristics in deep, intermediate, and shallow water is presented in Table 2.III.

2.5.1.3 Wave energy

Progressive surface water waves possess both potential and kinetic energy. The potential energy arises from the free surface displacement and the kinetic energy from the water particle motions. From linear wave theory it can be shown that the average potential energy per unit surface area for a free surface sinusoidal displacement, restored by gravity, is

$$\overline{E}_p = \frac{\rho g H^2}{16} \quad [45]$$

Likewise the average kinetic energy per unit surface area is

$$\overline{E}_k = \frac{\rho g H^2}{16} \quad [46]$$

and the total average energy per unit surface area is

$$\overline{E} = \overline{E}_p + \overline{E}_k = \frac{\rho g H^2}{8} \quad [47]$$

The unit surface area considered is a unit width times the wavelength L so that the total energy per unit width is

$$\overline{E}_T = \frac{\rho g H^2 L}{8} \quad [48]$$

The total energy per unit surface area in a linear progressive wave is always equi-partitioned as one half potential and one half kinetic energy.

Energy flux is the rate of energy transfer across the sea surface in the direction of wave propagation. The average energy flux per wave is

$$F_E = ECn \quad [49]$$

where

$$n = \frac{C_g}{C} = \frac{1}{2}\left(1 + \frac{2kd}{sinh(2kd)}\right) \quad [50]$$

and C_g is the group speed defined as the speed of energy propagation. In deep water n ≈ 1/2 and in shallow water n ≈ 1 indicating that energy in deep water travels at half the

TABLE 2.III Summary of Linear Wave Theory Wave Characteristics

Relative Depth	*Shallow Water* $\frac{d}{L} < \frac{1}{20}$	*Transitional Water* $\frac{1}{20} < \frac{d}{L} < \frac{1}{2}$	*Deep Water* $\frac{d}{L} > \frac{1}{2}$
Wave Profile	Same as for transitional water	$\eta = \frac{H}{2} cos[kx - \sigma t] = \frac{H}{2} cos\,\theta$	Same as for transitional water
Wave Celerity	$C = \frac{L}{T} = \sqrt{gd}$	$C = \frac{L}{T} = \frac{gT}{2\pi} tanh(kd)$	$C = C_0 = \frac{L}{T} = \frac{gT}{2\pi}$
Wavelength	$L = T\sqrt{gd} = CT$	$L = \frac{gT^2}{2\pi} tanh(kd)$	$L = L_0 = \frac{gT^2}{2\pi} = C_0 T$
Group Velocity	$C_g = C = \sqrt{gd}$	$C_g = nC = \frac{1}{2}\left[1 + \frac{2kd}{sinh(2kd)}\right] \cdot C$	$C_g = \frac{1}{2} C = \frac{gT}{4\pi}$
WATER PARTICLE VELOCITY			
Horizontal	$u = \frac{H}{2}\sqrt{\frac{g}{d}} cos(\theta)$	$u = \frac{H}{2}\sigma \frac{cosh(k(d+z))}{sinh(kd)} cos(\theta)$	$u = \frac{\pi H}{T} e^{kz} cos(\theta)$
Verticle	$w = \frac{H\pi}{T}\left(1 + \frac{z}{d}\right) sin(\theta)$	$w = \frac{H}{2}\sigma \frac{sinh(k(d+z))}{sinh(kd)} sin(\theta)$	$w = \frac{\pi H}{T} e^{kz} sin(\theta)$
WATER PARTICLE ACCELERATIONS			
Horizontal	$a_x = \frac{H\pi}{T}\sqrt{\frac{g}{d}} sin(\theta)$	$a_x = \frac{H}{2}\sigma^2 \frac{cosh(k(d+z))}{sinh(kd)} sin(\theta)$	$a_x = 2H\left(\frac{\pi}{T}\right)^2 e^{kz} sin(\theta)$
Vertical	$a_z = -2H\left(\frac{\pi}{T}\right)^2 \left(1 + \frac{z}{d}\right) cos(\theta)$	$a_x = -\frac{H}{2}\sigma^2 \frac{sinh(k(d+z))}{sinh(kd)} cos(\theta)$	$a_z = -2H\left(\frac{\pi}{T}\right)^2 e^{kz} cos(\theta)$
WATER PARTICLE DISPLACEMENTS			
Horizontal	$\xi = -\frac{HT}{4\pi}\sqrt{\frac{g}{d}} sin(\theta)$	$\xi = -\frac{H}{2} \frac{cosh(k(d+z))}{sinh(kd)} sin(\theta)$	$\xi = -\frac{H}{2} e^{kz} sin(\theta)$
Vertical	$\zeta = \frac{H}{T}\left(1 + \frac{z}{d}\right) cos(\theta)$	$\zeta = \frac{H}{2} \frac{sinh(k(d+z))}{sinh(kd)} cos(\theta)$	$\zeta = \frac{H}{2} e^{kz} cos(\theta)$
Subsurface Pressure	$p = \rho g(\eta - z)$	$p = \rho g \eta \frac{cosh(k(d+z))}{cosh(kd)} - \rho g z$	$p = \rho g \eta e^{kz} - \rho g z$

speed of the wave while in shallow water energy propagates at the same speed as the wave.

2.5.2 Wave Shoaling

Waves entering shallow water, with the exception of minor losses due to breaking, conserve energy. This is in part due to the fact that the wave period remains constant as the wave encounters varying water depths. However, wave celerity decreases as a function of depth and correspondingly the wavelength shortens. Therefore, the easiest conservative quantity to follow is the energy flux (given in equation 49), which remains constant as a wave shoals. Equating energy flux in deep water (Ho, Co) to energy flux at any shallow water location (Hx' C_X) results in the general shoaling relation

$$\frac{H_x}{H_0} = \left(\frac{1}{2n}\frac{C_0}{C_x}\right)^{1/2} \quad [51]$$

where n is calculated from (50) and C_0/C_x, can be obtained from equation 34. Thus, by knowing the deep-water wave height and period (H_0, T_0) and the bathymetry of a coastal region, the shoaling wave characteristics (H_x, C_x, L_x) can be calculated at any point, x, prior to breaking. One limitation to equation 51 is that it does not directly incorporate the effect of deep-water angle of approach to the coast.

2.5.3 Wave Refraction

It can be shown that a deep water wave approaching a coast at an angle α_0 and passing over a coastal bathymetry characterized by straight and parallel contours, refracts according to Snell's law

$$\frac{\sin\alpha_0}{C_0} = \frac{\sin\alpha}{C} \quad [52]$$

Since the phase speed of waves in shallow water decreases as depth decreases, application of Snell's law to a plane parallel bathymetry indicates that wave crests tend to turn and align with the bathymetric contours.

Considering two or more wave rays (orthogonals perpendicular to approaching wave crests) propagating shoreward over a plane parallel bathymetry, it is possible to have the rays either converge or diverge. Under these conditions, the energy per unit area may increase (convergence) or decrease (divergence) as a function of the perpendicular distance of separation between adjacent wave rays b_0 and b_x. Using the geometric relationships shown in Figure 2.20, equation 51 can be modified to account for convergence and divergence of wave rays as

$$\frac{H_x}{H_0} = \left(\frac{1}{2n}\frac{C_0}{C_x}\right)^{1/2}\left(\frac{b_0}{b_x}\right)^{1/2} \quad [53]$$

also written as

$$H_x = H_0 K_s K_R \quad [54]$$

where K_S is the shoaling coefficient and K_R the refraction coefficient. This expression is equally valid between any two points along a wave ray in shallow water.

2.5.4 Wave Diffraction

Wave diffraction is a process by which energy is transferred along the crest of a wave from an area of high energy density to an area of low energy density. There are two important ocean engineering applications of diffraction.

First, as wave rays converge and diverge in response to natural changes in bathymetry the K_R term in equation 54 will increase or decrease, respectively.

As a result, energy will move along the wave crest from areas of convergence to areas of divergence. It is, therefore, necessary to consider the effects of both refraction and diffraction when calculating wave height transformation due to shoaling.

The fundamental equations used to carry out diffraction calculations are based on the classical Sommerfeld relation

$$\eta = \frac{AkC}{g}\cosh(kd)\left|F(r,\Psi)\right|e^{ikCt} \quad [55]$$

where

$$\left|F(r,\Psi)\right| = \frac{H_D}{H_i} = K' \quad [56]$$

K' is the diffraction coefficient, H_D is the wave height in the zone affected by diffraction and H_i is the incident wave height outside of the diffraction zone.

The second, and perhaps most important, application of wave diffraction is that due to wave-structure interaction. For this class of problems, wave diffraction calculations are essential for obtaining the distribution of wave height in harbors or behind engineered structures in either deep or shallow water. There are three primary types of wave-structure diffraction important to ocean engineering (Figure 2.21): (a) diffraction at the end of a single element (semi-

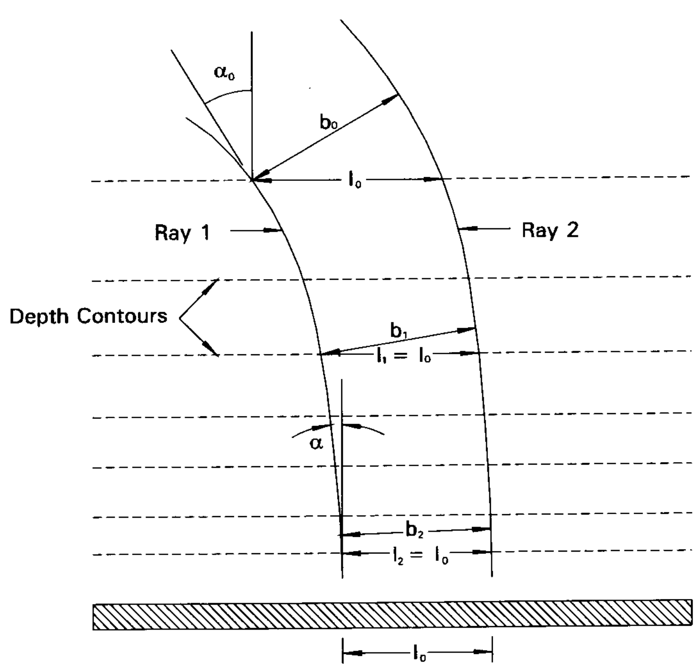


Figure 2.20 Geometric Diagram of Wave Refraction Over a Planar Sloping Beach

infinite); (b) diffraction through a pair of structures such as a harbor entrance (gap diffraction); and (c) diffraction around an offshore structure.

The methods of solution for all three of these wave-structure interactions are similar, but are restricted by some important assumptions. For each case there is a geometric shadow zone on the sheltered side of the structure, a reflected wave zone on the front or incident wave side of the structure, and an *illuminated* zone in the area of direct wave propagation.

In most natural coastal regions, bathymetry is both irregular and variable along a coast and the techniques for estimation of the resultant wave field due to refraction and diffraction involve the approximate solution of non-linear partial differential equations by various numerical techniques (11-15).

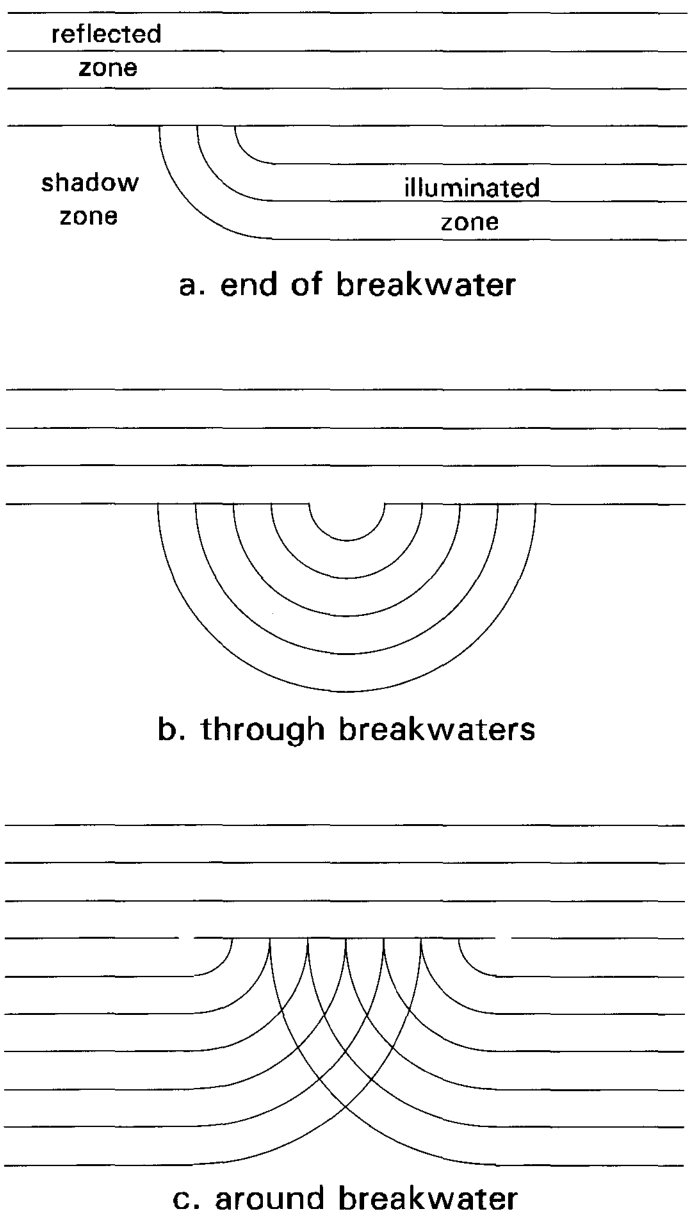


Figure 2.21 Three Examples of Wave Defraction Patterns

2.5.5 Wave Breaking

Waves propagating into shallow water tend to experience an increase in wave height to a point of instability at which the wave breaks, dissipating energy in the form of turbulence and work done on the bottom. There are three classifications of breaking waves. Spilling breakers are generally associated with low sloping bottoms and a gradual dissipation of energy. Plunging breakers are typically present over steeper sloping bottoms and have a rapid, often spectacular, *explosive* dissipation of energy. Surging breakers are associated with very steep bottoms and a rapid narrow region of energy dissipation. A widely used classic criteria (16) applied to shoaling waves relates breaker height,R_b, to depth of breaking, d_b' through the relation

$$H_b = 0.78 d_b \qquad [57]$$

However, this useful estimate neglects important shoaling parameters such as bottom slope (m) and deep water wave angle of approach (α_0). Dalrymple et al (15) used equation 57 and McCowan's breaking criteria to solve for breaker depth, d_b, distance from the shoreline to the breaker line, x_b, and breaker height, H_b, as

$$d_b = \frac{1}{g^{1/5}\kappa^{4/5}}\left(\frac{H_0^2 C_0 \cos\alpha_0}{2}\right)^{2/5} \qquad [58]$$

$$x_b = \frac{d_b}{m} \qquad [59]$$

and

$$H_b = \kappa d_b = \kappa m x_b = \left(\frac{\kappa}{g}\right)^{1/5}\left(\frac{H_0^2 C_0 \cos\alpha_0}{2}\right)^{2/5} \qquad [60]$$

where $\kappa = H_b/d_b$. Dalrymple et al (16) compared the results of a number of laboratory experiments with equation 60 and found that it under-predicts breaker height by approximately 12% (with $\kappa = 0.8$). Wave breaking is still not well understood and caution is urged when dealing with engineering design in the active breaker zone.

2.5.6 The Nature of the Sea Surface

Within the region of active wind-wave generation, the sea surface becomes very irregular in size, shape and direction of propagation of individual wave forms. This disorderly surface is referred to as sea. As waves propagate from the region of active generation by the wind, they tend to sort themselves out into a more orderly pattern. This phenomenon, known as dispersion, is due to the fact that longer period (or wavelength) waves travel faster, while short period waves lag behind. Swell is a term applied to waves, which have propagated outside the region of active wind wave generation. These waves are more regular in shape with a narrow direction of travel and are characterized by a narrow distribution of periods.

Given these distinctions between sea and swell it is reasonable to expect that the statistical description of the sea surface would be very different from place to place and over time. The wave spectrum is a plot of the energy associated with each frequency component of the sea surface.

Perhaps Kinsman (18) has best described the ocean wave spectrum. In his classic treatise entitled, *Wind Waves: Their Generation and Propagation on the Ocean Surface,* he entitled his chapter on ocean wave statistics:

"The Specification of a Random Sea ... in which we discover a viewpoint from which chaos reveals a kind of order."

This subheading implies that a statistical order may exist in a seemingly chaotic sea surface. This may be attempted by evaluating the amount of energy associated with regular components that are envisioned to comprise the irregular sea surface. Hence, the assumption is made that the total energy, E, per unit area of an irregular sea is adequately represented by the sum of the energies associated with each of the chosen regular wave components. The accuracy of this assumption is obviously dependent upon the number of regular wave components chosen to represent the actual irregular sea surface. Hence, the sum of the variances from still water level, of the component waves, is combined to approximate the total variance of the irregular sea. For wave recordings (records) of finite length the variance of the record is given by

$$E = \sigma^2 = \frac{1}{N}\Sigma\zeta_i^2 \qquad [61]$$

where ζ_i^2 are measured values of deviations from still (mean) water level and N is the total number of observations contained within the record. Equivalently

$$E = \sigma^2 = \int_0^\infty S(\omega)d\omega \qquad [62]$$

where the total area of the spectrum, S, provides a measure of the severity of the sea surface. As will be seen later, the energy per unit area of the sea surface is proportional to the variance. When multiplied by the fluid density and by gravity the total wave energy per unit area is given by

$$e_w = \rho g \sigma^2 = \rho g E \qquad [63]$$

Because the spectral area is proportional to the wave energy, the variance spectrum is sometimes referred to as the energy spectrum of the sea surface.

The difference between sea and swell spectra is shown schematically in Figure 2.22. Note that the sea spectrum is typically broadly distributed in frequency while the swell spectrum is narrowly distributed in frequency, tending toward monochromatic waves.

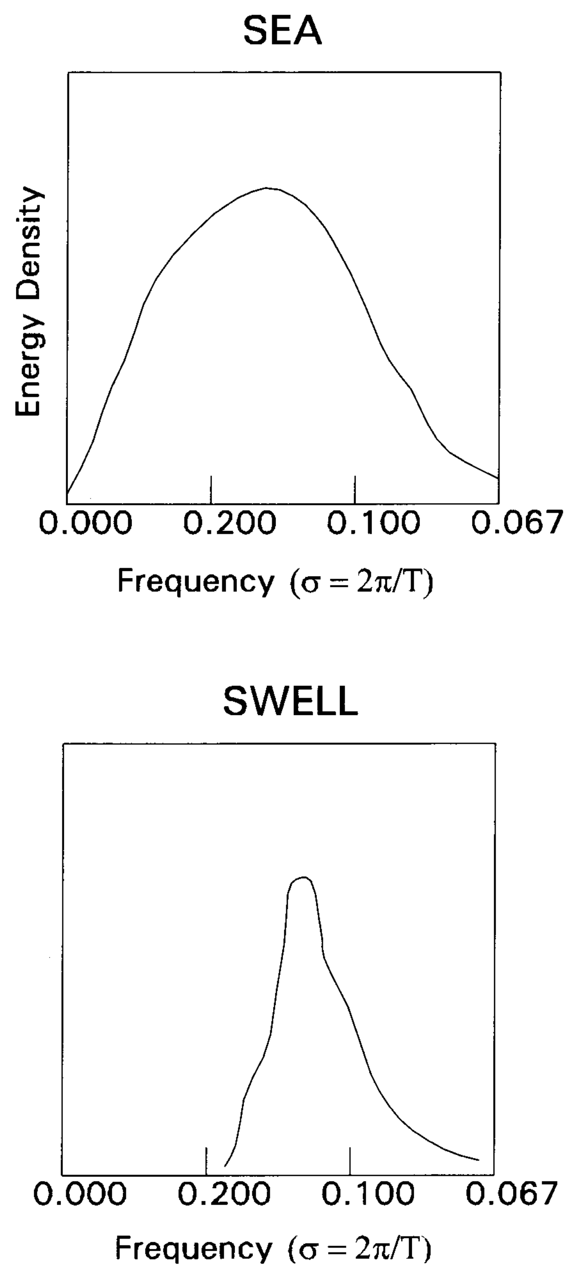


Figure 2.22 Wave Energy Spectra Showing a Typical Distribution for Sea Versus Swell

The directional distribution of wave energy propagation is given by the two-dimensional directional wave energy spectrum. Just as in the case of the one-dimensional wave energy spectrum, the two-dimensional spectrum provides a plot of wave energy versus frequency; however, the spectrum is further defined by the direction of wave propagation.

Actual recordings of wave propagating in the open sea reveal a significant order to an apparent random process. The vertical displacement from the peak of the wave crest to the bottom of either the preceding or following wave trough is defined as the wave height, H. Many studies from many locations worldwide have demonstrated that the distribution of wave heights most closely follows the Rayleigh probability density function. The probability density function of apparent wave height, $p(h_w)$, is given as

$$p(h_w) = \frac{h_w}{4E} exp\left(\frac{-h_w^2}{8E}\right) \qquad [64]$$

Hence, once this probability density function of the sea surface has been accepted, it is very easy to define many important and useful statistical properties of the open sea. Perhaps one of the most useful measures of wave height is the significant wave height, $H_{1/3}$ or H_s. The significant wave height is defined as the average of the one-third largest waves of the record. For engineering practice, this simple representation of the sea has acquired wide spread use. These are the *most significant* waves in the design of ships and harbors and in the prediction of near shore sediment transport. A useful compilation, based upon the Rayleigh distribution, of these statistical measures is provided in Table 2.IV (19). Note that based upon the assumption that the conditions of the sea state under investigation remain statistically stationary, expected heights of the highest waves in the series may be predicted. This is a very powerful tool.

TABLE 2.IV Common Statistical Wave Height Measurements, Based On Rayleigh Distribution

Common Name	*Symbol*	*Relation*
Average apparent wave height	H_{avg}	$2.5\sqrt{E}$
Significant wave height	H_s or $H_{1/3}$	$4.0\sqrt{E}$
Ave of (1/10)-highest waves	$H_{1/10}$	$5.1\sqrt{E}$
Highest expected wave in		
50 waves		$6.0\sqrt{E}$
100 waves		$6.5\sqrt{E}$
500 waves		$7.4\sqrt{E}$
1000 waves		$7.7\sqrt{E}$
5000 waves		$8.6\sqrt{E}$
10 000 waves		$8.9\sqrt{E}$

2.5.7 Wave Prediction

The wave height and associated energy contained in the wind generated sea surface is generally dependent on three parameters: the speed ofthe wind measured at 10 m above the sea surface, U_{10}, the open water distance over which the wind blows or fetch length, x, and the length of time the wind does work on the sea surface or duration, t. The growth of a wind driven sea surface may be limited by either the fetch or duration, producing a sea state less than "fully arisen" (maximum energy) for a given wind speed.

One-dimensional wave prediction models generally consist of equations, which estimate wave height and wave period at a particular location and time as a function of fetch length and wind speed. Three examples of one-dimensional wave prediction formulae are provided in Table 2.Y. It should be noted that the wind speed utilized in these wave prediction models must be obtained from, or corrected to, a height of 10m above the water surface.

A widely used approximation for correcting a wind speed, measured at height z over the open ocean, to 10m is

$$U_{10} = U_z\left(\frac{10}{z}\right)^{1/7} \qquad [65]$$

If the wind speed is measured near the coast, the exponent used for this correction is 2/7. In the event that over water winds are not available, over land winds may be utilized, but need to be corrected for frictional resistance. This is due to the fact that the increased roughness typically present over land sites serves to modify the wind field. A concise description of this methodology is presented in the Shore Protection Manual, see U.S. Army Corps of Engineers (19) and a comparison of several methods is presented by Schwab and Morton (20).

Since the natural sea surface is statistically complex, the wave height is usually expressed in terms of the significant wave height. The significant wave period corresponds to the energy peak in the predicted wave spectrum. Other expressions for wave height which are commonly used in design computations are: H_{max}, the maximum wave height, H_{rms}, the root mean square wave height, H_{avg}, the average wave height, H_{10}, the average of highest 10 percent of all waves and H_1, the average of the highest 1 percent of all waves. The energy-based parameter commonly used to represent wave height is H_{IO}, which is an estimate of the significant wave height fundamentally related to the energy distribution of a wave train. Table 2.VI summarizes the relationship between these various wave height parameters.

When predicting wave generation by hurricanes, the determination of fetch and duration is much more difficult due to large changes in wind speed and direction over short time and distances scales. Typically, the wave field associated with the onset of a hurricane or large storm will consist of a locally generated sea superimposed on swell components from other regions of the storm, see U.S. Army Corps of Engineers (10).

2.5.8 Harbor Resonance

As waves from the open sea propagate into coastal regions, and into harbors in particular, significant wave-structure interactions can occur. As sea waves encounter coastal structures, proportions of the incident wave energy are reflected from, absorbed by and transmitted through these coastal fortifications. In the case of harbors, the relative portions of these three processes determine the degree to which the harbor provides a safe refuge.

Reflected wave energy within the harbor entrance, as well as from interior walls, can be a significant problem in some harbors. In addition, wave transmission through semi-permeable breakwaters (rubble mound) may also add to the interior reflected wave activity. When the interior dimensions of the enclosed harbor or entrance channel match the incident wavelength (or an integer multiple of the incident wavelength) harbor resonance may result. Resonance is the constructive interference of successive waves resulting in enhanced wave amplitudes. Hence, when the incident wave periods match the natural period of the harbor, or some portion of the harbor, large amplification factors may be realized. This can result, in extreme cases, of larger waves inside the harbor than outside.

In general, the complication of solving the governing equations for harbor resonance, subject to the boundary conditions of irregular geometry, variable absorption, reflection and transmission at the walls, variable water ~epth and a realistic incident wave spectra, requires a numerical solution be employed. Such numerical schemes are available in the literature. For example, see Mei and Agnon (21) or Xu et al (15).

TABLE 2.V One-dimensional Wave Prediction Formulas

SMB	$H_s = 0.283 g^{-1} U^2 \tanh\left[0.0125\left(\frac{gx}{U_{10}^2}\right)^{0.42}\right]$ $T = 7.54 g^{-1} U \tanh\left[0.077\left(\frac{gx}{U_{10}^2}\right)^{0.25}\right]$
JONSWAP	$H_s = 0.0016 g^{-0.5} U x^{0.5}$ $T = 0.286 g^{-0.67} U^{0.33} x^{0.33}$
Donelan	$H_s = 0.00366 g^{-0.62} U^{1.24} x^{0.38} (\cos\phi)^{1.24}$ $T = 0.54 g^{-0.77} U^{0.54} x^{0.23} (\cos\phi)^{0.54}$
Definitions	H_s = significant wave height (in meters) T = peak energy wave period (in seconds) U = wind speed at 10 m height (in meters per second) x = fetch length (in wave direction for Donelan formulas) ϕ = angle between wind and waves g = 9.8 meters per second

2.5.9 Internal Waves

Just as waves freely propagate at the air-water interface, so also in a stratified ocean do waves propagate at sharp density interfaces. Typically, at the base of the thermocline or halocline internal wave motions are common. The frequency (or period) of these wave motions is controlled by the relative strength of the vertical stratification, with the frequency of wave motion decreasing with depth below the density contrast or with weakening stratification. Also, analogous to the surface wave problem, the degree of deformation of the interface (wave height) is a measure of the potential energy residing in the wave. In the internal wave case, since the density contrast across the interface is much less than that

TABLE 2.VI Summary of Approximate Statistical Wave Height Relations

	$\bar{H}$	H_{rms}	H_s	H_{10}	H_1	H_{max}
$\bar{H}$	—	0.89	0.63	0.49	0.38	0.33
H_{rms}	1.13	—	0.71	0.56	0.42	0.38
H_s	1.60	1.42	—	0.79	0.60	0.53
H_{10}	2.03	1.80	1.27	—	0.76	0.68
H_1	2.67	2.37	1.67	1.31	—	0.89
H_{max}	2.99	2.65	1.87	1.47	1.12	—

across the air-water interface, internal waves can grow to enormous heights in representing the same potential energy of the deformation. However, internal wave propagation speeds are slow. The phase speed for internal wave propagation in arbitrary depth water is given by:

$$C_i^2 = \frac{(\rho'' - \rho')(g/k)}{\rho'' \, coth(kh'') + \rho' \, coth(kh')} \qquad [66]$$

Where p is the fluid density, h is the water depth and , and ~ represent the upper and lower fluids, respectively.

Internal waves are now known to be common phenomena and propagate in specific ocean regions. Their propagation is important to vertical mixing within the ocean and to submerged vehicle operations. It is believed by some that the loss of the U.S. Submarine *Thresher* SSN 593 off the east coast of the United States in 1963 was the result, in part, of internal wave propagation. This region of the North Atlantic, near Georges Bank, is now known as a primary breeding ground of storm induced internal waves. The heights of these internal waves have been recorded in excess of 150 meters.

2.6 ASTRONOMICAL TIDES OF THE OCEANS

The astronomical tides of the ocean are caused by the gravitational attraction between the earth and moon and to a lesser extent, the earth and sun. Since the earth rotates on its axis, which is tilted at an angle to the plane of its orbit about the sun and the moon revolves about the earth, it is necessary to first understand these astronomical relationships. The gravitational attraction between these bodies result in tidal motions in all large bodies of fluid including the oceans, large lakes of the world, atmosphere and earth's mantle.

The earth's orbit about the sun is a nearly circular ellipse with the sun located at one foci. The earth is closest to the sun during Northern Hemisphere winter and farthest away during Northern Hemisphere summer. An entire orbit of the sun is completed in one tropical year, 365 days, 5 hours, 48 minutes, and 45.7 seconds and the distance from the sun to the earth ranges from 147 to 152 million km. The axis of the earth is tilted 66.5 degrees to the plane of the earth's orbit and the direction of the earth rotation on its axis is in the same sense as its direction of revolution about the sun.

The moon and the earth rotate about a common point, located within the earth, with the moon also revolving around the earth in the same direction as the earth revolves around the sun. Hence, it takes the moon, one synodic month (29 days, 12 hours, 44 minutes, and 28.28 seconds) to make one revolution about the earth, relative to the sun. This is the time for the moon to appear to pass through all of its phases as viewed from earth. During this time the distance between the earth and the moon varies from 357 000 to 384 500 kIn.

Since, the earth rotates on its axis in the same direction as the earth-moon system revolves around the sun; the moon passes over the same point on earth a little later each day. The length of the lunar day (diurnal) is 24 hours, 50.47 minutes, which is the dominant tidal period.

Finally, the plane of the moon's orbit about the earth is not in the same plane as that of the earth about the sun. These two planes intersect at an angle of about 5.1 degrees. Hence, it should now be apparent that a significant number of unique but related periodicities must be combined to reproduce a complete picture of the astronomical tidal forcing.

The resulting tide producing force, for both the earth-moon and earth-sun systems, generates a bulge of fluid on

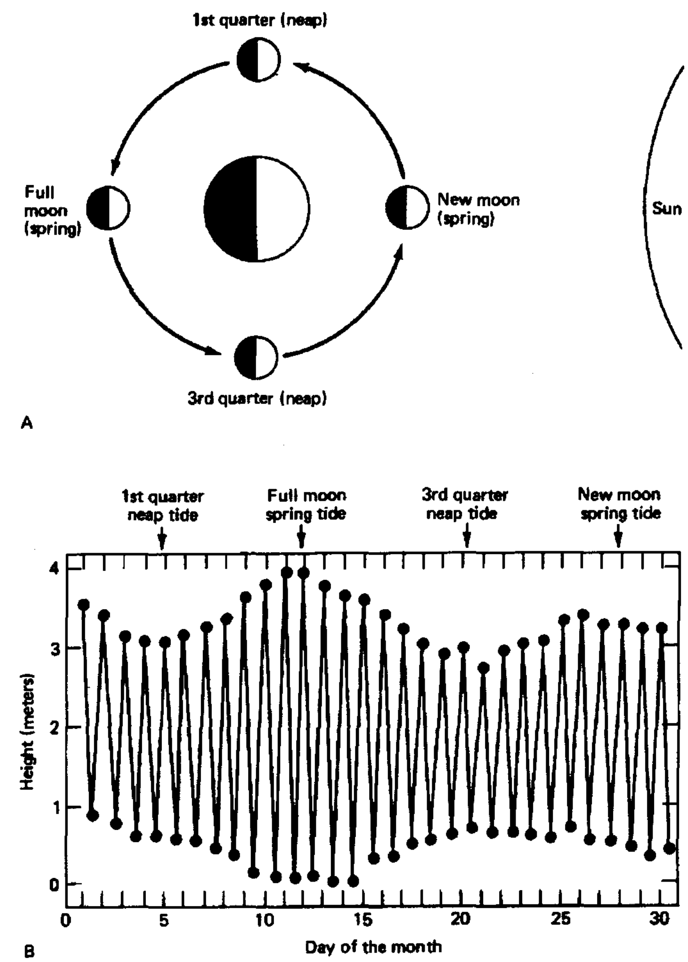


Figure 2.23 A Schematic of the Earth-Moon-Sun System and Resultant Tidal Ranges for Various Celestial Configurations over the Course of One Lunar Month (22)

both the side of the earth facing the corresponding body as well as the side facing away. As the earth rotates through these bulges, this results in the time between encountered *high water* equal to one half of the lunar day (semi-diurnal) or 12 hours and 25.235 minutes. Twice per month, the bulges associated with the earth-moon system will align with those created by the earth-sun system to produce large, *spring* tides. Similarly, twice per month these two tide-producing forces will be in quadrature, producing a low tidal range or *neap* tide. Figure 2.23 shows the relationship between the earth-moon-sun system and resultant tidal range over a 30-day period.

In predicting the elevation of the sea surface for a particular harbor, the practical problem reduces to one of considering ten semi-diurnal components, six, diurnal components and five, long period components.

Due to the phase of these primary components, as well as variation in the ocean basin geometry and depth, the tide experienced at any location will vary substantially throughout the lunar month. This may include shifting from a dominance of semi-diurnal to diurnal components. Figure 2.24 provides a comparison of tides at four different locations.

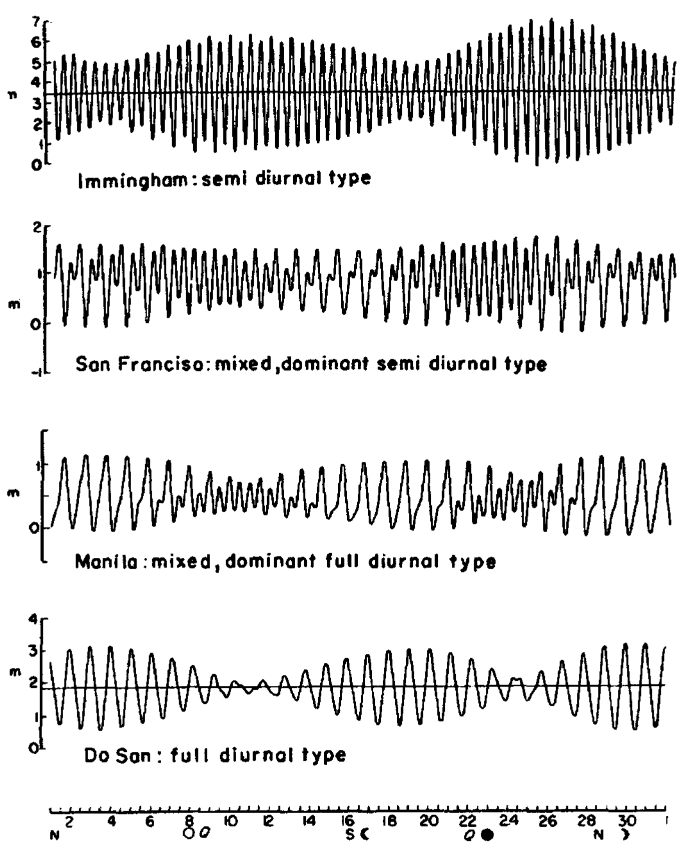


Figure 2.24 Tides at Four Locations Showing a) Dominant Semi-diurnal Tide, b) Mixed Tide, and d) Fully Diurnal Tide (23)

We have established thatthe dominant, open ocean, tidal period is 12 hours, 25.235 minutes, which corresponds to two *tidal bulges* on opposite sides of the earth. Hence, the corresponding wavelength of this *tidal wave* is half the circumference of the earth. Therefore, even in the deepest portions of the ocean basins these waves, by definition, are shallow water waves.

2.6.1 Tides in Shallow Water and Tidal Currents

In addition to the periodic rise and fall of water levels, tides in shallow water can also produce substantial tidal currents. In the linear approximation, tides are shallow water waves, obeying the linearized equations presented in Section 2.5.1. The shallow water of the continental margins serves to modify the propagation characteristics of these tidal bulges. Tidal heights and horizontal particle velocities (tidal currents) are of most interest.

Tidal heights in confined bays may reach extreme elevations. The classic examples of the Bay of Fundy and Cook Inlet, Alaska are well known worldwide. In the Bay of Fundy, in particular, spring tides typically reach a range in excess of 15 meters. During these episodes tidal currents can often reach velocities in excess of 8 knots (16 kmlhr).

Tide prediction tables are available for most parts of the world. In the U.S., both tide height and current prediction tables are available from the U.S. Department of Commerce, National Oceanic and Atmospheric Administration (NOAA), National Ocean Service, Washington D.C.

2.6.2 Wave/Current Interaction

Waves propagating on, or across a current, can experience substantial modifications and exchanges of energy. Phillips (24) discusses both weak and strong interactions between waves themselves and with the environment through which they propagate. Weak interactions occur, when the time scales of evolution of wave characteristics is large compared to the individual wave periods. With these weak interactions, wave properties change slowly in time or space. The cumulative effect over large scales, however, may be drastic. In contrast, strong interactions occur almost instantaneously and include the phenomena of wave breaking, the deformation of short waves riding on swell, and the rapid response of waves interacting with an abrupt change in an underlying current. These latter cases are of particular interest in navigating in shallow coastal waters.

Given a train of short waves with wave number k and intrinsic frequency 00, the steady kinematic conservation equation is given by:

$$\frac{\partial k}{\partial t} + \nabla(\sigma + k \cdot u) = 0 \qquad [67]$$

where u, is the near surface horizontal velocity of the fluid. Conservation of wave action provides

$$\frac{\partial\left(\frac{E}{\sigma}\right)}{\partial T} + \nabla \cdot \left\{\left(u + C_g\right)\left(\frac{E}{\sigma}\right)\right\} = 0 \qquad [68]$$

where E is the energy density of the wave train and C_g is the wave group velocity.

Inspection of these results provides some interesting cases. For a current with velocity varying in the direction of flow, u=u(x), such as ebb flow from an estuary, two cases exist. For waves traveling in the same direction as the current, u>O, the wave number k is reduced (wavelength is increased) and the wave height decreases. For waves encountering an adverse current, u<O, their wavelength is shortened, their group velocity is decreased and they become less able to propagate against the current. If the current is of sufficient strength, wave blocking may occur and the waves appear stationary in space. The energy density of the wave train increases and is limited by wave breaking.

A similar set of conditions can be evaluated for the case of waves encountering a shear current, u=u(y). In general, for the case of waves propagating with a component in the direction of the current, wave direction will refract to become more aligned with the current, wavelength will increase and wave energy density will decrease. For the case of wave propagation with a component adverse to the current, refraction will turn the wave train more normal to the current with a decrease of wavelength and an increase in wave energy density.

Similar phenomena have been observed for tidally driven flow interacting with bottom topographic irregularities. As a spatially variable current (tidal rip) is established over a submarine feature, surface wave variations should be expected. These variations in the local wave field can be severe and pose a potential hazard to navigation.

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2.8 RECOMMENDED RESOURCES

The following titles are recommended reading for further details pertaining to the topics presented within this chapter:

Dynamics of the Upper Ocean, 2nd ed., Owen M. Phillips, Cambridge University Press, 1977.

Introduction to Geophysical Fluid Dynamics, Benoit Cushman-Roisin, Prentice Hall, 1994.

Introduction to Physical Oceanography, John A. Knauss, Prentice Hall, 1978.

Principles of Ocean Physics, John R. Apel, Academic Press, 2000.

Principles of Physical Oceanography, Gerhard Neumann and Willard J. Pierson, Jr., Prentice Hall, 1966.

Shore Protection Manual, U.S. Army Corps of Engineers, CERC/WES,1984.

"Water Wave Mechanics for Engineers and Scientists," Rogert G. Dean and Robert A. Dalrymple, *World Scientific,* 1991.

Wind Waves, Blair Kinsman, Prentice Hall, 1965.

Chapter 3

The Marine Industry

Tim Colton

3.1 INTRODUCTION

The goal of this chapter is to describe the industrial context in which ships are designed and built. While some understanding of the history of the marine industry is essential, because much of what drives the industry has its roots in history, it is believed that adequate coverage is provided in other publications (1-6). Because the unusually long economic life of a ship creates a business cycle that lasts for over 30 years, the structure and practices of the marine industry are always influenced in some way by the events of the preceding 3D-plus years. In fact, many events in the history ofthe past 58 years, since the end of World War II, are still relevant.

Although the marine industry in the United States is in some ways isolated from those of other nations, the marine industry as a whole is both international and multinational. As a result, it is also necessary to examine the structure of the industry worldwide.

This chapter is divided into three parts. Section 3.2 describes the universe of ships, boats and other vessels that are designed, built and operated by the marine industry; Section 3.3 describes the marine industry itself; and Section 3.4 summarizes the current state of the marine industry.

3.2 THE WORLD FLEETTODAY

3.2.1 Introduction

The world fleet of ships and other floating structures can be defined in five broad categories:

1. *cargo ships-self-propelled,* commercial, oceangoing ships that are primarily designed to carry the world's trade,
2. *passenger vessels-self-propelled,* commercial, vessels that are primarily designed to carry passengers and vehicles,
3. *naval vessels-self-propelled* ships, boats and craft operated by navies, coast guards and other military or quasi-military agencies,
4. *other self-propelled vessels-ships* and craft used for catching, processing and transporting fish and fish products; ships and craft used for the offshore exploration and production of oil and gas; tugs and towboats; and all other commercial vessels that do work rather than carry cargo or passengers, and
5. *barges and other inshore vessels--Dceangoing* and inland barges, self-propelled river-trading vessels and a range of miscellaneous floating structures.

The various types and subtypes of ships and craft in each of these categories are discussed in the next five sub-sections.

The structure of the fleet as a whole is summarized in round numbers in Table 3.1.

3.2.2 Cargo Ships

Cargo ships can be described in three categories:

1. liquid cargo carriers (tankers)-ships that carry liquid cargoes such as oil, refined petroleum products, chemicals and liquefied gas in bulk,
2. dry bulk cargo carriers (bulkers)-ships that carry dry cargoes such as grain, coal and ore in bulk, and

3. general cargo carriers-ships that carry cargoes in other than bulk forms, that is, packaged, palletized, containerized or wheeled.

Table 3.II summarizes the world fleet of cargo ships at the beginning of 2002, in numbers of vessels and in tonnage (both GT and DWT) (7).

In the discussion of the structure of the fleet by type that follows, a distinction is made between ships that are greater than Panamax in breadth (about 32.2 m) and those that are not.

The significance of this distinction lies not in the operating flexibility defined by a ship's ability to transit the Panama Canal, but in the number of shipyards that have the ability to build or to drydock a ship of this size. As will be seen in the next section, there is a marked distinction between the relatively small number of shipyards that can build or drydock ships that are wider than Panamax and the relatively large number of shipyards that cannot build or drydock ships that are wider than Panamax.

Attention is also drawn in the ensuing discussion to the average age of each sector of the fleet. As a generalization, naval architects design ships to last up to 30 years. The average age of the world cargo fleet is 18 years, which suggests an average life of over 30 years. In addition, the growth in the number of ships in the fleet means that there are more younger ships in the fleet than older, so the average life of a cargo ship must, in fact, be well over 30 years. This means that, if the fleet never grew in total size and there were no cyclical fluctuations in its composition, about 3% of its capacity would be renewed each year. Since the fleet does grow, however, its average age ought to be less than 18 and more than 3% of its total capacity ought to be built new each year.

In addition to this continuing requirement to renew the fleet, the size of the fleet grows over the long term at about 3% a year, measured in GT, and at just over 2% a year, measured in numbers of ships. This growth, which is illustrated in Figures 3.1 and 3.2, results from the inexorable increase in world trade, which is driven by consumption, which is, in turn, driven by population growth. The significant difference between the rate of growth of tonnage and the rate of growth of the number of ships is a reflection partly of the increasing size of all types of cargo ships and partly of the increasing efficiency of the shipping industry.

Cyclical fluctuations in fleet renewal result in variations in the average age: if the age of one particular sector of the fleet is above average, for example, that sector is overdue for renewal, and vice versa. In addition, if the average age of a particular sector is decreasing, its renewal rate must be increasing, and vice versa. An examination of these two trends provides a helpful indicator, at a macro level, of shipbuilding market opportunities.

TABLE 3.I The World Fleet as a Whole

Ship Type Category	*Number*
Cargo Ships	40 000
Passenger Vessels	7500
Naval Ships and Craft	26 500
Other Self-Propelled Vessels	42 000
Barges and Other Inshore Vessels	238 000
Total	**354 000**

TABLE 3.II The World Fleet of Cargo Ships

Ship Type	*Number*	*GT (mm)*	*DWT (mm)*
Liquid Cargo	11 083	196	334
Dry Bulk Cargo	6476	168	297
General Cargo	22 739	157	175
Totals	**40 298**	**521**	**806**

TABLE 3.III- The World Fleet of Tankers

Ship Type	*Number*	*GT (mm)*	*DWT (mm)*
Crude Carriers	1793	131	242
Product Carriers	5191	25	42
Chemical Carriers	2598	19	30
LNG Carriers	128	11	8
LPG Carriers	1025	9	11
Other Types	348	1	1
Totals	**11 083**	**196**	**334**

3.2.2.1 Liquid cargo carriers

Ships that carry liquid cargoes in bulk, or tankers, are classified by the cargo they carry, which generally determines their internal design. The four main categories are oil carriers, chemical carriers, gas carriers and *others*, but the oil carrier and gas carrier fleets include two distinct subsets and there are some gray areas in the breakdown.

Table 3.m summarizes the world fleet of liquid cargo carriers, or tankers.

The oil carrier fleet is really two fleets. Most large tankers are relatively simple ships that only carry crude oil, while most of the smaller ones carry refined products and have much more complex cargo-handling systems. The dividing line between the two groups is in the region of 60 000 tons, which also corresponds roughly to the dividing line between ships that are more or less than Panamax beam, but there are exceptions to both these rules. In addition, many of the more sophisticated product carriers, especially the smaller ones, can also carry chemicals.

At the beginning of 2002, there were 1793 *crude carriers* in the world fleet, with a total deadweight capacity of about 242 million tonnes and an average size of about 135 000 deadweight tonnes. Of this fleet, about 25% are ofless than 60 000 deadweight tonnes and are probably not more than Panamax in breadth; about 50% are of at least 60 000 tonnes but less than 175 000 tonnes, and about 25% are of at least 175 000 tonnes and are referred to either as very large crude carriers (VLCCs) or as ultra large crude carriers (ULCCs). The average age of the crude carrier fleet is about 13 years and rising: the renewal rate in 2001 was about 5.0% and falling.

Companies in Greece, Japan, Norway and the U.S. dominate the ownership of crude carriers.

At the beginning of 2002, there were 5191 *product carriers* in the world fleet, with a total deadweight capacity of about 42 million tonnes and an average size of about 8000 deadweight tonnes. Of this fleet, only about 2% are of at least 60 000 tonnes and potentially more than Panamax in breadth. The average age of the fleet is about 22 years and rising: the renewal rate in 2001 was about 2.2% and falling.

Companies in Greece, Japan, the U.S., China, Russia, and Singapore dominate the ownership of product carriers.

At the beginning of 2002, there were 2598 *chemical carriers* in the world fleet, with a total deadweight capacity of about 30 million tonnes and an average size of about 11 700 deadweight tonnes. Just as many product carriers can also carry chemicals, so many of the simpler chemical carriers can also carry refined products and some of the1ll also carry LPG. Of this fleet, only about 1% are of at least 60 000 tonnes and potentially more than Panamax in breadth. The average age of the fleet is about 14 years and rising: the renewal rate in 2001 was about 6.0% and falling.

Companies in Norway, Japan, the U.S., and Greece dominate the ownership of chemical carriers.

The gas carrier fleet is really two fleets-liquefied natural gas carriers, (LNG carriers, or LNGCs), and liquefied petroleum gas carriers, (LPG carriers or LPGCs).

At the beginning of 2002, there were128 *liquefied natural gas carriers,* with a total capacity of about 14.3 million cubic meters and an average size of about 112000 cubic meters. Virtually all the LNGCs are more than Panamax in breadth, almost all of them being of about the same size, around 125 000 to 140 000 cubic meters in capacity. The average age of the LNGC fleet is about 14 years and steady: the renewal rate in 2001 was about 1.0% and rising.

Companies in Japan and Bermuda dominate the ownership of LNG carriers.

At the beginning of 2002, there were 1025 *liquefied petroleum gas carriers*, with a total capacity of about 14 million cubic meters and an average size of about 13 800 cubic meters. None of these LPGCs is larger than Panamax. The average age ofthe LPGC fleet is about 16 years and rising: the renewal rate in 2001 was about 4.8% and rising.

Companies in Norway and Japan dominate the ownership of LPG carriers.

At the beginning of 2002, there were 348 tankers of *other types* in the world fleet, with a total deadweight capacity of about 0.8 million tonnes and an average size of about 2200 deadweight tonnes. None ofthese ships is more than Panamax in breadth. This category includes several small subtypes, such as tankers that are specially designed to carry water, fruit juices, molasses, vegetable oils, wine, asphalt

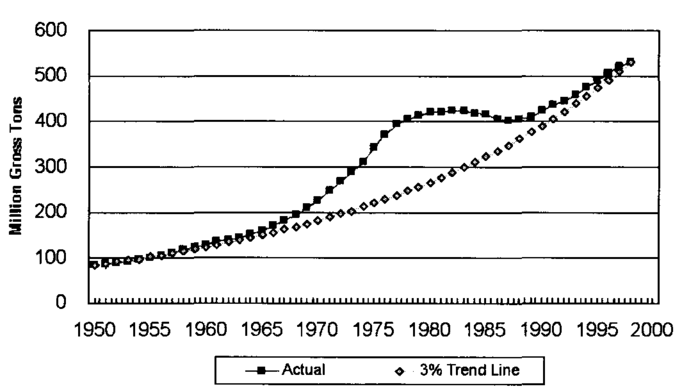

Figure 3.1 Growth in Tonnage

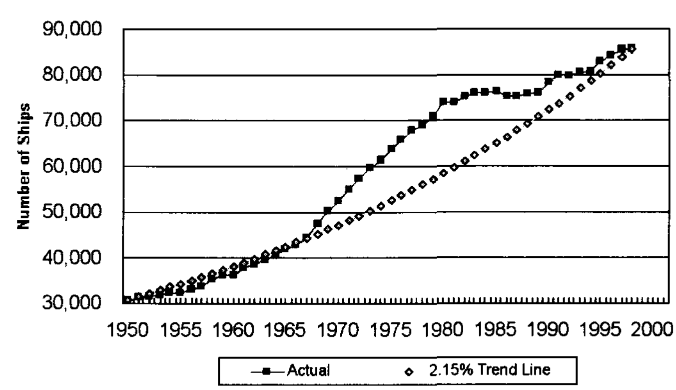

Figure 3.2 Growth in Number of Ships

and molten sulfur. The average age of this fleet is about 24 years and rising: there is currently very little renewal of this sector.

Companies in Japan, Norway and the U.S. dominate the ownership of other types of tankers.

. Tankers are relatively simple ships to build and virtually all that are Panamax or larger are now built in Japanese, Korean or Chinese shipyards. European yards still build some ofthe higher-value, more complex types, such as chemical carriers, gas carriers and the special cargo carriers. In addition, the smaller sizes of tanker are more likely to be built in shipyards located in the same geographic region as their owners.

Design information for liquid cargo ships is presented as follows:

Chapter 29 - Oil Tankers
Chapter 31 - Chemical Tankers
Chapter 32 - Liquefied Gas Carriers

3.2.2.2 Dry bulk cargo carriers

Dry bulk cargo carriers, or bulkers, are classified by the cargo they carry, which generally determines their internal design. The four main categories are standard dry bulk carriers, which carry coal, ore and grain, combination carriers, which can carry either dry bulk cargoes or crude oil, self-unloaders, and others.

Table 3.IV summarizes the world fleet of dry bulk cargo carriers, or bulkers.

At the beginning of 2002, there were 5000 *standard dry bulk carriers* in the world fleet, with a total deadweight capacity of about 268 million tonnes and an average size of about 53 600 deadweight tons. Of this fleet, about 70% are of less than 60 000 tonnes and probably less than Panamax in breadth, while about 20% are of at least 60 000 tonnes but less than 125 000 tonnes, and the remaining 10% are very large bulk carriers (VLBCs) of over 125 000 deadweight tonnes.

The average age of the bulker fleet is about 14 years and steady: the renewal rate in 2001 was about 7.5% and rismg.

Companies in Greece, Japan, China, Hong Kong, and South Korea dominate the ownership of standard bulkers.

At the beginning of 2002, there were 201 *combination carriers* in the world fleet, with a total deadweight capacity of about 14 million tonnes and an average size of about 71 900 deadweight tonnes. Of this fleet, about 40% are of less than 60 000 tonnes and probably less than Panamax in breadth, while another 40% are of at least 60 000 tonnes but less than 125 000 tonnes, and the remaining 20% are of over 125 000 tonnes. The average age of the combination carrier fleet is about 16 years and rising rapidly: the renewal rate in 2001 was only 1.0% and fallin.g.

Companies in Norway and Greece dominate the ownership of combi carriers.

At the beginning of 2002, there were 171 *self-unloaders* in the world fleet, including the Great Lakes ships, with a total deadweight capacity of about 6 million tonnes and an average size of about 33 000 deadweight tonnes. Of this fleet, only about 10% are greater than Panamax in breadth. The average age of the se1f-unloader fleet is about 26 years and rising: the renewal rate in 2001 was 3.3% and rising.

Companies in the U.S. and Canada dominate the ownership of self-unloaders.

At the beginning of 2002, there were 1104 bulkers of *other types* in the world fleet, with a total deadweight capacity of about 9 million tonnes and an average size of about 8200 deadweight tonnes. This category includes specialized designs that carry such cargoes as cement, wood chips and urea. None of these ships is more than Panamax in breadth. The average age of this fleet is about 18 years and rising: the renewal rate in 2001 was about 2.4% and rising.

Companies in Japan dominate the ownership of other types of bulkers.

Bulkers are the simplest of ships to build and virtually

TABLE 3.IV The World Fleet of Bulkers

Ship Type	*Number*	*GT (mm)*	*DWT (mm)*
Standard Bulkers	5000	150	268
Combi Carriers	201	8	14
Self-Unloaders	171	3	6
Other Types	1104	7	9
Totals	**6476**	**168**	**297**

TABLE 3.V The World Fleet of General Cargo Ships

Ship Type	*Number*	*GT (mm)*	*DWT (mm)*
Break-Bulk	16 446	53	75
Containerships	2756	67	77
Refrig. Cargo	1407	7	7
Roll-On/Roll-Off	1871	28	14
Other Types	259	2	2
Totals	**22 739**	**157**	**175**

all that are Panamax or larger are now built in Japanese, Korean or Chinese shipyards. Only the smallest sizes ofbulker are likely to be built in shipyards located in the same geographic region as their owners.

Design information for dry bulk cargo carriers is presented in Chapter 33.

3.2.2.3 General cargo carriers

General cargo carriers are classified by their configuration. The five main categories are break-bulk cargo ships, which carry cargo in packages, in bundles or on pallets; containerships, which carry cargo in standard-sized boxes loaded in cellular holds; refrigerated cargo *(reefer)* ships, which carry perishable cargoes in insulated holds or in insulated containers in uninsulated holds; roll-on/roll-off *(RO-RO)* ships, which carry wheeled cargo; and *others,* which include ships that are specially designed to carry livestock, barges and unusually heavy loads. Table 3.V summarizes the world fleet of general cargo carriers.

At the beginning of 2002, there were 16446 *break-bulk cargo ships* in the world fleet, with a total deadweight capacity of about 75 million tonnes and an average size of about 4600 deadweight tonnes. Of this fleet, about 75% are of less than 5000 deadweight tonnes, designed essentially for short sea trades, and there are none that are larger than Panamax in breadth. The average age of the break-bulk cargo ship fleet is about 22 years and rising: the renewal rate in 2001 was about 1.3% and falling.

The ownership of break-bulk ships is concentrated in China, Greece, Norway, Germany, Russia, and Japan.

At the beginning of 2002, there were 2756 *container ships* in the world fleet, with a total deadweight capacity of about 77 million tonnes or about 5.3 million twenty-foot equivalent units (TEUs). The average size of this fleet is about 27800 deadweight tonnes or about 1930 TEUs and increasing. Of this fleet, about 12% are of over 4000 TEUs and probably more than Panamax in breadth: these post-Panamax ships represent about 32% of the total fleet's capacity. The average age of the containership fleet is only about 10 years and falling: the renewal rate in 2001 was about 11.5% and falling.

The ownership of container ships is dominated by companies in Germany, with almost 25% of the total capacity, but Taiwan, Japan, Denmark, Greece, the U.S., China, the United Kingdom, Singapore, and South Korea all have significant fleets.

At the beginning of 2002, there were 1407 *refrigerated cargo ships* in the world fleet, with a total deadweight capacity of about 7 million tonnes or about 9.4 million cubic meters of insulated capacity. The average size of the reefer ship fleet is about 5200:deadweight tonnes or about 6700 cubic meters capacity. Virtually all the ships in this fleet are under 15000 deadweight tonnes, or about 19000 cubic meters capacity, and there are none that are larger than Panamax. The average age of the reefer ship fleet is about 19 years and rising: the renewal rate in 2001 was 2.1% and falling.

Companies in Japan and Greece dominate the ownership of reefer ships.

At the beginning of 2002, there were 1871 *roll-on/roll-off ships* in the world fleet, excluding passenger-vehicle ferries, with a total deadweight capacity of about 14 million tonnes and an average size of about 7300 deadweight tonnes. Virtually all the ships in this fleet are less than 45 000 deadweight tonnes and there are none that are larger than Panamax. The average age is about 17 years and steady: the renewal rate in 2001 was 2.4% and falling.

Companies in Japan, with over a third of the total capacity, dominate the ownership of ro-ro ships but Norway and Sweden also have significant fleets.

At the beginning of 2002, there were 259 *general cargo carriers of other types* in the world fleet, with a total deadweight capacity of about 2 million tonnes and an average size of about 7800 deadweight tonnes. The average age of this fleet is about 25 years and rising rapidly: the renewal rate in 2001 was negligible and falling.

Companies in the Netherlands and the U.S. dominate the ownership of other types of general cargo ship.

Container ships are relatively simple ships to build and virtually all that are Panamax or larger are now built in Japanese, Korean or Chinese shipyards. European yards still build their share of the other types, however, and the smaller sizes of general cargo ship are much more likely to be built in the same geographic region as their owners.

Design information for general cargo carriers is presented in:

Chapter 27 - Multi-purpose Cargo Ships
Chapter 28 - Reefer Ships
Chapter 35 - RO-RO and RO-LO Ships
Chapter 36 - Container Ship

3.2.3 Passenger Vessels

Passenger vessels are classified by the type of service that they offer, which generally determines their internal design. There are four main categories:

1. *cruise ships-ships* that carry passengers only, operating oceanic services that are determined by the tourism market,
2. *deep-sea* ferries-ships that carry either passengers only

or both passengers and vehicles (cars, trucks and trailers), operating on regularly scheduled services and providing overnight accommodation,

3. *short-sea ferries*-vessels of conventional design that carry either passengers only or passengers and vehicles, on regularly scheduled services but not providing overnight accommodation: these ferries are not generally oceangoing and have speeds that do not generally exceed 25 knots, and
4. *fast ferries*-vessels that are specifically designed for high-speed service and carry at least 50 passengers, at speeds in excess of 25 knots.

Table 3.VI summarizes the fleet of passenger ships (8).

At the beginning of 2002, there were 372 *cruise ships* in the world fleet identified by Lloyd's Register, totaling about 9 million gross tons: the average size of this fleet is about 24 000 gross tons and the average age is about 23 years. Industry sources counted 255 large cruise ships at the same point in time, with a total of 244 250 berths, an average capacity of about 950 berths per ship (9).

The average size of the cruise ship fleet is increasing rapidly and the average age is falling, for two reasons. First, the new ships that have been added in recent years and that are under construction are much bigger than in the past, averaging 60000 gross tons and 1500 berths, and reaching up to as large as 140000 gross tons and 4000 berths. Second, the cruise industry's growth rate in recent years has been about 10% a year (9): the older ships are now being retired and these ships are mostly much smaller than the new ships that replaced them.

Companies in the *V.S.* dominate the ownership of cruise ships.

A feature of this market sector is the concentration of its construction: there are only four major builders of large cruise ships-all in Europe-and their combined output is only six or seven ships a year.

It should be noted here that there are no longer any true passenger liners in the world fleet. The business of carrying passengers by sea for any distance that requires more than a single night on board ship has been entirely eliminated by the universal and relatively inexpensive availability of air travel. There are a few ships in the cruise fleet that started life as liners, most notably the *Queen Elizabeth 2* and the *Norway (ex-France)* and both these ships still undertake North Atlantic crossings, a route not normally associated with cruising. In addition, Cunard's current newbuilding, to be called *Queen Mary* 2, is designed to be a liner as well as a cruise ship. Very few of the transatlantic passengers on these ships are traveling from Britain to the *V.S.* on business, however, or purely to get from one country to the other: they are on vacation.

At the beginning of 2002, there were 2973 *deep-sea ferries* in the world fleet. The ships in this fleet vary a good deal in size: they average about 5 000 gross tons, with a passenger capacity of about 300. They have an average age of about 22 years which has been rising, but the sector's renewal rate is about 7%. Deep-sea ferries generally operate in markets that are relatively well protected from the incursions of other modes of transportation. These markets include those for low-cost transportation services to remote, less developed islands and territories, and those for regional cruising. In the first case, the availability of economical and reliable transportation to outlying areas is a necessary part of regional development. In the second case, ferry services that also serve vacationers enjoy a unique and growing market niche, linked to tourism and recreation rather than to transportation. This construction market is also highly concentrated; many of these ships are European-built, but Asia is increasing its market share.

Companies in Greece, Italy, and Japan dominate the ownership of cruise ferries.

At the beginning of 2002, there were at least 2710 *short-sea ferries* in the world fleet. This figure may understate the size of the fleet, however, because many small ferries are owned by government agencies, which do not have to register the vessels, and many small ferries are so small as to escape counting.

The vessels in this fleet vary a good deal in size, ranging up to as much as 20 000 gross tons but averaging only about 500. Passenger capacities range up to 2200, with an average of about 200. Their average age is about 20 years and steady, as the renewal rate is about 2.3 %. Most of these vessels provide low-cost transportation services in competition with land transportation modes. As these ships are relatively simple to build, the market for their construction is universal: short-sea ferries are built everywhere.

Companies in Indonesia and Japan dominate the ownership of short-sea ferries.

TABLE 3.VI The World Fleet of Passenger Vessels

Ship Type Category	*Number*
Cruise Ships	372
Deep-Sea Ferries	2973
Short-Sea Ferries	2710
Fast Ferries	1400
Total	**7455**

There is no reliable single source of information on the structure of the fast ferry fleet. Excluding the many hydrofoils built in the former Soviet Union, most of which are still extant but no longer operating, over 1600 fast ferries have been built since the tecnhnology was introduced. Assuming that the older vessels have been scrapped, there are probably still at least 1400 active vessels, including about 700 multihulls, about 300 hydrofoils, about 250 monohulls, and about 150 surface-effect craft (10).

In general, the vessels in this category have much higher performance characteristics than either deep-sea or short-sea ferries, which are conventional in design. This higher performance takes the form either of higher speed or of more comfortable ship motions in offshore operating environments, or both.

Fast ferries do not vary much in size, ranging up to about 2500 gross tons and averaging about 300. Their speeds average over 30 knots and their passenger capacities about 250. This fleet represents the cutting edge of marine technology and its average age is only about 10 years. The nature of these vessels implies some extension of the passenger transportation markets that are served, either as an extension of vessel capabilities to serve a larger or more distant region or as an improvement in vessel performance to create or improve market share in competition with other modes of transportation. In the case of hydrofoils, the nature of the technology effectively limits the application of these vessels to more sheltered waters and thus forces them into closer competition with these other modes. The largest concentration of catamarans is in China, Norway, and Australia, hydrofoils in Italy and Greece, monohulls in Japan, and SES craft in China and Hong Kong.

The construction of high-speed ferries is unusually distributed, geographically. Most of the development of catamaran and monohull technology has taken place in Australia, a country not generally thought of as on the leading edge of maritime technology, and Australian shipbuilders are the major builders, extending their influence to other world regions through licensing arrangements. The leading developers of hydrofoils, however, are in Russia and Italy, and these two countries still dominate their construction.

By contrast, although the surface-effect ship was a British invention, its subsequent development for military applications was mostly in the U.S., and for commercial applications was in the Far East.

Design information for passenger vessels is presented in:

Chapter 37 - Passenger Ships
Chapter 38 - Ferries
Chapter 44 - High Speed Surface Craft
Chapter 45 - Catamarans
Chapter 46 - SWATH and Trimarans

TABLE 3.VII The World Fleet of Naval Ships and Craft

Ship Type Category	*Number*
Aircraft Carriers	30
Submarines	600
Large Surface Combatants	800
Small Surface Combatants	8150
Mine-Warfare Ships and Craft	1070
Amphibious-Warfare Ships and Craft	5200
Seagoing Auxiliaries	1700
Service and Other Craft	8900
Total	**26 450**

3.2.4 Naval Ships and Craft

The world fleet of naval ships and craft includes not only warships of all types and sizes but also those non-military ships and craft that are owned by the world's navies and by other quasi-naval government agencies, such as coast guards, customs services, immigration services and fisheries protection services.

There are about 26 500 naval ships and craft in the world fleet, in eight major categories:

1. aircraft carriers,
2. submarines,
3. large surface combatants,
4. small surface combatants,
5. mine-warfare ships and craft,
6. amphibious-warfare ships and craft,
7. seagoing auxiliaries, and
8. service and other craft.

Design information for all of the above naval ship types except the last is provided in detail in Chapter 54 - Naval Vessels and Chapter 55 - Submarines.

The world fleet of naval ships and craft is summarized in round numbers in Table 3.VII (11).

The totals shown in Table 3.VII are conservative, for three reasons:

1. there is considerable uncertainty concerning the disposition of the former Soviet fleet,
2. it is very difficult to count the numbers of smaller vessels and service craft in some navies, including some of the largest, such as that of China, and

3. it is always difficult to determine which vessels are active, which are in reserve but could be reactivated and which are beyond reactivation or have actually been scrapped; it is particularly difficult in the wake of post-Cold War downsizing and in the case of many of the developing economies.

It should be noted also that there is overlap between the different ship type categories. Some navies tend to overstate. A World War II-vintage tug is described as an offshore patrol vessel, for example, or an 8 m launch as a patrol boat.

As a result, the values presented in Table 3.VII are no more than an indication of the size of the world fleet.

3.2.4.1 Aircraft carriers

Aircraft carriers are the only naval vessels that can be described as very large. They are designed primarily for the projection of naval power over wide areas, an objective only the United States and the former Soviet Union have attempted since World War II and the Soviet Union preferred to invest in submarines. The only significant carrier force today is that of the U.S. Navy: the only other navy with a nuclear-powered big-deck carrier is that of France, which also has one conventionally powered big-deck carrier and one V/STOL carrier. The Indian and Brazilian navies each still have a WWII-vintage ex-British carrier to help them control the Indian and South Atlantic oceans, respectively.

Vertical/short take-off and landing (V/STOL) or *jump-deck* carriers are increasingly popular in the second tier of the world's navies: there are now 10 of these vessels operational or under construction, six in Western European Navies, two in the Russian Navy, one in the Indian Navy, and one, specially designed to be able to undertake multiple missions, in the Thai Navy.

At the beginning of 2003, the only countries with aircraft carriers under construction or planned were Britain, Italy and the U.S.

3.2.4.2 Submarines

The alternative Cold War means of power projection was the nuclear-powered submarine, whether in its strategic form, as a carrier of intercontinental ballistic missiles, or its tactical form, as a hunter-killer. With the end of the Cold War, the number of nuclear submarines has been greatly reduced and is still declining: the current figure is 187, but this is almost certainly over-stated. The only nuclear-powered submarines other than those of the U.S. and Russia are those of the other three permanent members of the Security Council, Britain, France, and China, and these are also the only other countries with nuclear-powered submarine building programs.

The non-nuclear submarine, although spurned by the U.S., is increasing in popularity elsewhere, as an effective and economical method of coastal patrol. There are now over 40 nations with non-nuclear submarine fleets, including three in Africa, ten in Asia, one in Australasia, two in the Middle East, six in Eastern Europe, eleven in Western Europe, and eight in the Americas. The fleet totals over 400.

Construction of non-nuclear submarines, both conventional diesel and air-independent, is more concentrated: at the beginning of 2003, at least 40 boats were under construction, by shipyards located in 13 countries-Brazil, China, France, Germany, Greece, India, Italy, Japan, Pakistan, Russia, South Korea, Spain, and Turkey (12).

3.2.4.3 Large surface combatants

With the end of the Cold War, the need for large surface combatants-battleships, cruisers, destroyers and frigates-has dwindled. The battleship is no more and the cruiser is going the same way: there are only three ships so described outside the U.S. and Russian Navies, one each in the navies ofItaly, Peru and Ukraine. At the beginning of 2003, there were no longer any cruisers under construction anywhere in the world.

Similarly, only 21 navies now count destroyers in their fleets and the total fleet is only 240 ships. Four of these 21 navies (Egypt, Mexico, South Korea, and Taiwan) operate 20 WWII-era ships, while another eight (Argentina, Australia, Chile, Greece, India, Pakistan, Poland, Romania) operate another 20 ships made excess by either the U.S., British, or Soviet Navies since WWII. This leaves only 12 navies (Britain, Canada, China, France, Germany, India, Italy, Japan, South Korea, Romania, Russia, and the U.S.) operating 200 purpose-built destroyers.

Frigates are more popular, although the number of this type is also declining: there are about 520 such ships operated by 56 navies, the greatest concentration being in Europe, whose navies collectively operate 170, followed by China and the U.S., each with about 40.

Construction of large surface combatants is fairly concentrated: in early 2003 there were about 55 destroyers and 65 frigates under construction. The destroyers were being built in Britain, China, France, India, Italy, Japan, South Korea, and the U.S., while the frigates were being built in Australia, Brazil, Britain, China, Denmark, France, Germany, India, the Netherlands, Russia, Singapore, Spain, Taiwan, and Turkey (12).

3.2.4.4 Small surface combatants

Small combatants are employed in a variety of roles, both military and quasi-military. Corvettes and guided-missile patrol vessels are generally employed by national navies in force projection and national defense roles, but because of their relatively small size, rarely go beyond a nation's home waters, including the extended economic zone (EEZ). Smaller and less sophisticated patrol craft are generally employed by national navies in coastal, inshore, and riverine areas, and by law enforcement agencies such as Coast Guards, immigration services, customs services, and police forces.

The number of craft that an individual nation requires, and their degree of sophistication, depends on such factors as the length ofthe nation's coastline, the number of major ports, the size ofthe offshore area and the nation's perception of the value of its offshore resources, such as oil and gas reserves or fisheries. The nature and volume of commercial shipping within the offshore area also contribute to the demand, as do the nation's relations with its neighbors.

There are about 1400 corvettes, offshore patrol vessels, large, missile-equipped patrol craft, and similar ships in the world's navies. The concentrations are in the fleets of Japan, China, Taiwan, the U.S., India, Mexico, Germany, South Korea, and Greece.

There are about 6750 small combatants in the world fleet: these cover a broad range of sub-types and include numerous vessels that are classified by their owners as patrol craft but are, in reality, no more than small boats. The vessels in this fleet also range in size considerably. The great bulk of them are smaller than 1000 displacement tons and the average size is about 265 tons. Their average speed is over 30 knots and the average crew size is 25. The average age of this fleet appears to be close to 17 years, but this figure may be misleading, because the year of build of many of the smaller vessels is not always known and, in some cases, only a range of years of delivery of a large class of vessels is known.

Small combatants are, of course, found everywhere: for about 50 countries, this is the only type of vessel that they possess. The largest fleets outside the U.S. are those of North Korea, Thailand, Venezuela, Japan, Brazil, Indonesia, China, Saudi Arabia, Italy, Mexico, Greece, Taiwan, Iraq, South Korea, Turkey, Argentina, Colombia, Sri Lanka, and Thailand. By contrast, many countries with extensive coastlines seem to be under-equipped for coastal patrol duty.

Construction of corvette-sized vessels is fairly concentrated; at the beginning of 2003, there were fewer than 20 under construction, in Brazil, Germany, India, Italy and Malaysia. Construction of small surface combatants is much less concentrated but is still dominated by a small number of companies: at the beginning of 2003, about 150 boats were under construction in about 20 countries (12).

3.2.4.5 Mine-warfare ships and craft

Mine-waifare ships are highly specialized types of ships used almost entirely in defensive roles. In general, mine-warfare ships are used to find and/or to clear mines that have been laid in a navigable waterway. they are not normally used for laying mines, which does not require a special vessel type. Something approaching a state of war must generally exist between the layer and the clearer of mines, although the layer may be a terrorist organization rather than a warring nation. A nation's need for mine countermeasures capability depends on the size and nature of its seaborne trade and the impact that any disruption of this commerce would have on its economy.

While the technology of mine warfare is constantly evolving and new and more sophisticated mines continue to be developed, it has been said that *no mine is ever obsolete.* As a result, mine hunters and clearers must be equipped for even the most primitive contact mine, which remains effective today and requires much the same clearance techniques as the most modem mines.

There are about 1070 mine-warfare vessels in the world fleet, including about 75 that are either under construction or the subject of specific construction plans.

The vessels in this fleet range in size considerably, but only a very few are over 1000 displacement tons and the average size is about 550 tonnes. The average speed is 14.5 knots and the average crew size is 40. About 42% of all mine-warfare vessels are made of wood, about 32% of GRP, about 13% of steel, and about 13% of some combination of materials. The average age of this fleet appears to be over 20 years, but as with patrol craft, this figure may be misleading.

The concentration of mine-warfare vessels is instructive. The largest fleets are those of China, Sweden, Germany, Hungary, Japan, Turkey, and Romania. By contrast, many countries with major ports seem to be significantly under-protected. Several Middle Eastern, Central and South American countries have no mine-warfare vessels at all.

As with other types of naval vessels, the construction of mine-warfare craft is concentrated. At the beginning of 2003, mine-warfare vessels were under construction in Germany, Italy, Japan, Russia, South Korea, Spain, and Turkey (12).

3.2.4.6 Amphibious-warfare ships and craft

Amphibious-waifare ships and craft include both the large assault ships and the landing craft that they carry. These vessels represent a specialized form of military transportation capability that was developed during and after World War II for use in amphibious operations. The nature of this function necessarily implies that their purpose is offensive and, in the current geo-political environment, there are few scenarios for which a major nation might feel the need to be prepared to mount an amphibious assault. As a result, there are few countries apart from the U.S. and Russia that operate significant numbers of large assault ships.

There are about 340 assault ships in the world fleet, the largest fleets being those of the U.S., the countries of the European Union, and Russia.

The construction of assault ships is highly concentrated: at the beginning of 2003, ships were under construction, in Britain, Italy, Japan, Singapore, South Korea, Spain, and the U.S. (12).

Landing craft are much more versatile than their parent ships and can be used for law enforcement and other police functions, and for inter-island transportation, especially in countries which have scattered island systems, or which have piracy or terrorism problems.

The level of technology associated with landing craft is not high. Although the U.S. has invested in large numbers of air-cushion vehicles for this mission, the resultant craft has not made all other designs obsolete, because of its high cost.

There are close to 5000 landing craft in the world fleet. The vessels in this fleet do not vary much in size, because many of them were built to standard designs: the average size is about 500 tonnes, the average speed is about 18 knots and the average crew size is 18. The average age of this fleet is apparently about 25 years, but as with patrol vessels and mine-warfare craft, this figure may be misleading.

The geographic distribution of the ownership oflanding craft is instructive. The largest owners of landing craft are the U.S., Sweden, Singapore, Malaysia, Taiwan, China, North Korea, and Britain. About 75 countries own at least one, but most have only a very few, suggesting a lack of confidence in their usefulness. It is interesting to speculate as to why a navy would own just one landing craft.

Many countries that might be expected to appreciate their value seem under-equipped and some, particularly in Central America and the Caribbean, have none at all.

The construction of landing craft is much less concentrated than that of the larger ships: at the beginning of 2003, at least 100 boats were under construction worldwide (12).

3.2.4.7 Seagoing auxiliaries

Auxiliaries include a variety of ship types, most involving vessels that are slow compared to the combatant types and generally unarmed. Their functions include:

1. fleet replenishment and other combat logistic support activities,
2. oceanography, hydrography and surveying,
3. surveillance and intelligence gathering,
4. icebreaking, dredging, buoy tending and similar activities concerned with navigation channels,
5. fisheries research,
6. ocean towing, salvage and rescue services, and
7. military sealift and other logistic roles.

There are at least 1700 seagoing auxiliaries in the world fleet, about 70% of which are operated by Russia, the U.S., the countries of Western Eur6pe, and China.

As with other large naval ship types, the construction of seagoing auxiliaries is fairly concentrated: at the beginning of 2003, large ships were under construction only in Britain, Germany, India, and Japan (12).

3.2.4.8 Service and other craft

Service craft constitute an even more varied miscellany than auxiliaries. There are more than 100 specific types, the principal ones including:

1. buoy tenders,
2. fireboats,
3. lighters,
4. tugs,
5. drydocks,
6. rescue craft,
7. floating cranes,
8. floating repair shops, and
9. launches and motorboats.

The total number of these craft in any particular country varies generally with the size of both its navy and its economy.

It is possible to identify close to 9000 service craft in the world's navies, but since about 3500 of these are operated by the U.S., a figure of 5500 for the rest of the world is certainly understated. The vessels in this fleet are of every size and configuration, even within each type: many were built for missions unrelated to their present roles. Their average age is about 19 years.

Most service craft are of relatively simple design; their construction is almost universal.

3.2.5 Other Self-Propelled Oceangoing Vessels

The world fleet of *other* self-propelled ships includes four major groups.

1. vessels employed by the fishing industry,
2. vessels employed by the offshore energy industry,
3. tugs and towboats, and
4. all other types, including dredgers, research vessels, icebreakers, cable ships, etc.

Table 3.VIII summarizes this fleet (13).

3.2.5.1 Fishing industry vessels

Fishing industry vessels fall into two *categories-fish catchers* and *fishing industry support ships.*

The vast majority of commercial fishing vessels are fish catchers, of which there are about 23 000 that are over 100 gross tonnes. The average size of a fish catcher is about 450 gross tons but this is heavily influenced by a small number of large vessels: roughly 45% of the fleet is under 200 tons and another 35% is between 200 and 300 tons. The average age of this fleet is now about 22 years and rising rapidly: the renewal rate in 2001 was less than 1% and steady.

The balance of the commercial fishing fleet consists of about 800 ships that process and transport the catch. The average size of this fleet is about 2000 gross tons. Its average age is about 20 years and rising rapidly: the renewal rate in 2001 was negligible.

Commercial fishing is universal but the concentration of ownership is in the countries with the largest populations-the U.S., with over 3250 seagoing boats, Russia, with about 2000, Japan, with about 1500, and South Korea and Spain, each of which has about 1100.

The construction of fishing vessels is almost universal; most are built in their country or at least in their region of operation. Activity has been stagnant for several years, as a result of over-fishing in some regions and of some species, and fewer than 200 vessels a year have been built in recent years, a renewal rate of less than 1%. This figure is increasing, however, indicating the possibility of a recovery in demand. Any major replacement program is unlikely to be on a one-for-one basis, however as the industry is ripe for the development of fishing fleets that are both more efficient and more environmentally friendly.

TABLE 3.VIII The World Fleet of Other Oceangoing Vessels

Ship Type Category	*Number*
Fish Catchers	23 106
Other Fishing Vessels	842
Sub-total Fishing Industry Vessels	23 948
Offshore Service Vessels	3200
Other Offshore Vessels	975
Sub-total Offshore Industry Vessels	4175
Tugs and Towboats	9044
Research Vessels	846
Dredgers	1121
Other Types of Self-Propelled Vessel	2824
Sub-total Other Vessels	13 835
Total	41958

Design information Jor fishing vessels is presented in Chapter 41.

3.2.5.2 Offshore industry vessels

Offshore industry vessels are categorized by Lloyd's Register as either *offshore service vessels,* (OSVs), or *other offshore vessels.* In addition, many offshore industry vessels escape Lloyd's Register's net because they are either non-self-propelled, such as most mobile offshore drilling units, (MODUs), or because they are too small, such as crewboats.

At the beginning of 2003, Lloyd's Register identifies *2655 offshore service vessels* in the world fleet, a figure that is somewhat lower than that of about 3200 found in offshore industry directories, probably because in recent years a significant portion of this fleet has been laid up. In addition, the lower limit of size of 100 GT utilized by Lloyd's Register excludes most crewboats.

The principal types of OSVs are anchor-handling tug/supply boats, (about 1100), conventional supply boats (about 900), anchor-handling tugs (about 300), crewboats (about 150), and other types (about 750) (14).

Anchor-handling tug/supply boats (AHTSs) are preferred to separate tugs and supply boats in offshore oil and gas fields where distances are long and conditions can be severe. They are also the equipment of choice in the offshore oilfields that have been more recently developed.

There are about 1100 AHTSs in the world fleet. The vessels in this fleet do not vary much in size and there are large numbers of vessels of standard designs. AHTSs range up to about 3500 gross tons in size, with an average that is just under 1000. The installed power ranges up to 12000 kW, with an average of close to 6000, and their speed ranges between 10 and 17 knots, with an average of about 13 knots. There are no old vessels in this fleet: ages range up to 30 years and average about 16 years. The ownership of AHTSs is concentrated in the U.S., where activity is moving into deeper water, requiring much larger vessels; there are over 250 AHTSs in the U.S. alone (15).

Conventional supply boats without anchor-handling capability are still employed in preference to combination anchor-handling tug/supply boats in offshore oil and gas fields where distances are shorter and conditions are rarely severe.

There are about 900 conventional supply boats in the world fleet, ranging from large platform supply boats to small utility boats. The vessels in this fleet do not vary much in size and there are large numbers of vessels of standard designs. Supply boats range up to 3500 gross tons in size, with an average that is just over 1000. There are some old vessels in this fleet, with ages ranging up to 40 years and averaging about 17 years. The ownership of supply boats is concentrated in the U.S., which has over 500; no other country has a significant fleet.

Anchor-handling tugs without supply capability are still employed in preference to combination anchor-handling tug/supply boats in offshore oil and gas fields where distances are shorter and conditions are rarely severe.

There are about 300 anchor-handling tugs in the world fleet. The vessels in this fleet do not vary much in size and there are large numbers of vessels of standard designs. Anchor handling tugs range up to about 1750 gross tons in size, with an average that is just under 400. The installed power ranges up to 8700 kW, with an average of close to 3500, and their speed ranges between 10 and 16 knots, with an average of about 12 knots. There are a few very old vessels in this fleet but generally ages range up to 33 years and average about 19 years. The ownership of anchor-handling tugs is concentrated in the U.S., which has about 150.

Crewboats are used to shuttle personnel to and from offshore work sites close enough to shore to make the boat more economical than the helicopter.

There are only about 150 crewboats in the world fleet that are over 100 GT. There may be considerably more that are smaller. The vessels in this fleet do not vary much in size and there are large numbers of vessels of standard designs. Crewboats range between 42 and 56 meters in length and carry up to 80 passengers at speeds up to about 32 knots. There are a few very old vessels in this fleet but generally ages range from 15 to 25 years. The ownership of crewboats is heavily concentrated in the U.S.

There are about 750 *other types of OSV* in the world fleet, including *survey vessels,* of which there are about 250, and *stand-by/rescue vessels,* of which there are about 220.

Survey vessels are used either by the major offshore exploration companies or by the governments of nations with significant oil and gas reserves in their exclusive economic zone (EEZ).

Stand-by vessels are a fairly recent development, required in the North Sea and other European waters for only the past three years. Most of the first stand-by boats in service were converted fishing vessels and a definitive design of stand-by boat has yet to be developed. Companies in the U.S. dominate the ownership of the other types of OSv.

U.S. shipyards dominate the construction of OSVs. In the boom of the 1970s, U.S. yards built more than 75% of the world fleet; although many of those yards have since closed, the key players are all still active. At the beginning of 2003, there were about 80 boats on order, about 60% of which were on order from U.S. yards, with the remainder divided between Scandinavian and Far East yards.

At the beginning of 2003, Lloyd's Register identified *629 other offshore vessels* in the world fleet, a figure that is somewhat lower than that of over 975 that is found in offshore industry directories, because many of these vessels are not self-propelled. The principal categories are offshore drilling equipment, offshore construction equipment, and offshore production equipment.

Offshore drilling equipment includes drill ships, semi-submersibles, jack-ups, submersibles and drilling barges. At the beginning of 2003, there were about 650 offshore drilling rigs in the world fleet (16).

At the beginning of 2003 there were 39 *drill ships* in the world fleet. Most drill ships are ship-shaped vessels with full-scale propulsion that allows them to move freely between drilling locations. They have dynamic positioning systems and the latest can drill in water depths in excess of 3000 meters. The average age of this fleet is about 17 years but falling rapidly. New drill ships have been built in recent years in Britain, Spain, and Korea.

At the beginning of 2003, there were 171 *semi-submersibles* in the world fleet. Most semi-submersibles are very large rectangular structures supported by truss-connected columns and pontoons, with only enough of a propulsion system to allow them to move around within one drilling location. Many now have dynamic positioning systems and the largest can drill in water depths in excess of 2000 meters. The average age of this fleet is about 16 years but is expected to begin falling as the offshore exploration industry enters a period of rapid expansion that requires new rig construction both for growth and for replacement.

Many of the older semis have now been upgraded for deep-water operation and the first few vessels of a new generation have entered service. Semis being both large and complex, the construction of this new generation can be expected to be concentrated in large shipyards with proven capabilities. In recent years, new semis have been or are being built in France, Germany, Korea, Russia, Singapore and the U.S. The economics of this business are, however, driving this market to shipyards in Korea, Singapore and China.

At the beginning of 2003, there were 380 *jack-ups* in the world fleet. Most jack-ups are triangular structures supported on three legs, with only enough of a propulsion system to allow them to move around within one drilling location. The largest can drill in water depths of up to about 150 meters. The average age of this fleet is about 17 years and, as with the semi-submersible fleet, is expected to begin falling as the offshore industry simultaneously expands and replaces its older rigs. In recent years, new jack-ups have been or are being built in Korea, Singapore and the U.S., but as with semi-submersibles, the construction of a new generation of jack-ups can be expected to be concentrated in large Asian shipyards.

At the beginning of 2003, there were only 7 *submersibles* in the world fleet, most having been converted into semi-submersibles. Submersibles are rectangular structures supported by truss-connected columns, with only enough of a propulsion system to allow them to move around within one drilling location; the largest can drill in water depths of up to 25 meters. This fleet is now redundant and can be expected either to be converted to semi-submersible configuration or to be scrapped.

At the beginning of 2003, there were 52 non-inland *drill barges* in the world fleet, most of which are designed for work in Venezuela's Lake Maracaibo. Drill barges are rectangular vessels with no propulsion capabilities and are designed for operation in water depths of up to about 40 meters. The average age of this fleet is about 17 years and is falling rapidly, as several new units have been built in recent years. The construction of non-inland drill barges is heavily concentrated in U.S. shipyards.

Offshore construction equipment includes derrick barges, pipe-lay barges, and related vessels (17).

At the beginning of 2003, there were about 170 offshore construction vessels in the world fleet, divided between about 80 *derrick barges,* and about 90 *pipe-lay barges.* The fleet grows by about 10 units per year. Although the basic hull form is quite simple, these are increasingly complex and sophisticated vessels, construction of which is concentrated in Asian shipyards.

Offshore production equipment includes floating units that engage in production alone (FPU s), production, storage, and offloading (FPSOs), and storage and offloading (FSOs).

At the beginninig of 2003, there were about 155 floating offshore production vessels in the world fleet, divided between about 70 *FPUs,* and about 85 *FPSOs and FSOs,* many of which were converted from other types of equipment, usually large tankers. This fleet grows by about 20 units a year. Offshore production vessels are both very large and very complex; in addition, their mission requirements often involve lifetime service without dry-docking. As a result, construction of these vessels is concentrated in the more sophisticated Asian shipyards, but they are still often outfitted in the U.S. or Europe.

The ownership of offshore exploration, construction and production equipment is dominated by companies in the U.S., Norway, Britain, and Brazil, reflecting the concentration of offshore activity in the Gulf of Mexico, the North Sea, and Brazil.

The great size and high value of most offshore exploration, construction and production equipment means that their construction is dominated by major shipbuilding companies that operate large, sophisticated shipyards. Although this includes a few shipyards in the U.S. and Europe, the economics of shipbuilding ellsure that most of these vessels are built in Asian shipyards.

Design information for offshore industry vessels is presented in Chapter 42 - Offshore Support Vessels, and Offshore Drilling and Production is presented in Chapter 43 - Offshore Drilling and Production Vessels.

3.2.5.3 Tugs and towboats

A *tug* is essentially a tractor that floats. Most tugs are designed and built to minimize the weight and cost of the hull structure that is wrapped around the engine. Specialized tugs are generally larger than general purpose tugs because they carry larger crews and more equipment. Oceangoing tugs are designed primarily for deep-sea towing or salvage work and are larger and more powerful than inshore tugs, which are designed primarily for mooring and escort work in harbors and protected waterways. There is no breakpoint in the scale of size or power, however, above which 'lie oceangoing tugs and below which lie inshore tugs. The number of tugs with the same propulsion power declines fairly consistently from the most popular size, which is about 1000 kW (18).

The geographic distribution of the ownership of tugs is universal. There are tugs wherever there are ships, and no particularly significant conclusions can be drawn from the ownership structure, except that there are several large international tug operators.

General-purpose tugs are employed primarily in harbor work. They are short, simple and rarely have installed power over about 2600 kW. On these vessels, bollard pull is more important than free-running speed. Twin-screw propulsion is standard. The use of azimuthing or cycloidal propulsors is increasing. Oceangoing tugs are larger, with more freeboard, larger crews and crew accommodation. High free-running speed is more important than bollard pull. Twin-screw propulsion is standard: the use of controllable-pitch propellers and nozzles is common.

There are about 4300 general-purpose tugs in the world fleet. The vessels in this fleet vary a good deal in size and there are large numbers of vessels built to standard designs. General-purpose tugs range up to about 3000 gross tons in size, with an average of about 250. Their installed power ranges up to 9000 kW, with an average of 1400, and their speeds range between 5 and 22 knots, with an average of about 11 knots. There are large numbers of old vessels in this fleet. Ages range up to 111 years and average about 23 years.

General-purpose tugs are, of course, found almost everywhere. There are general-purpose tugs registered in at least 143 countries. Major concentrations are found in Britain, Canada, Greece, Indonesia, Italy, Japan, Korea, the Netherlands, Russia, Singapore, and the U.S ..

There are about 750 *firefighting tugs* in the world fleet. The vessels in this fleet vary less in size than general-purpose tugs and there are large numbers of vessels built to standard designs. Firefighting tugs range up to 1100 gross tons in size, with an average that is just short of 300. Their installed power ranges up to 6700 kW, with an average that is just short of 1870, and their speeds range between 8 and 17 knots, with an average of about 12 knots. There are the normal number of older vessels in this fleet. Ages range up to 58 years and average about 16 years.

As would be expected, firefighting tugs are also found almost everywhere: there are firefighting tugs registered in at least 92 countries. Major concentrations are found in-Australia, Britain, Indonesia, Italy, Japan, the Netherlands, Russia, and Spain.

There are about 400 *tractor tugs* in the world fleet. The vessels in this fleet vary less in size than general-purpose tugs and there are large numbers built to standard designs. Tractor tugs range up to 1100 gross tons in size, with an average of 300. Their installed powers ranges up to 5200 BHP, with an average of 2110, and their speeds range between 8 and 14 knots, with an average of about 11 knots. There are few old vessels in this fleet with ages ranging up to 35 years but the average is only about 12 years.

Tractor tugs are a relatively new development and are much less widely distributed than general-purpose or firefighting tugs. There are tractor tugs registered in only 42 countries. Major concentrations are found in Britain, Germany, Saudi Arabia, and the U.S.

There are about 400 *salvage tugs* in the world fleet. The vessels in this fleet vary a good deal in size and there are fewer vessels built to standard designs. Salvage tugs range up to about 5250 gross tons in size, with an average of just over 700. Their power ranges up to 18 650 kW, with an average of 3846, and their speeds range between 8 and 20 knots, with an average of about 13 knots. There are large numbers of old vessels in this fleet with age ranging up to 78 years and average about 21 years.

Salvage tugs are found in most maritime nations. There are salvage tugs registered in 55 countries. Major concentrations are found in China, Italy, Japan, and Russia.

There are about 50 tugs of *other types* in the world fleet. The vessels in this fleet vary a good deal in size and there are few vessels built to standard designs. The tugs in this miscellaneous category range up to about 1600 gross tons in size, with an average of 273. There are large numbers of old vessels in this fleet. Ages range up to 80 years and average about 18 years.

The construction of tugs is almost universal; most are built in their country or at least in their region of operation. At the beginning of 2003, there were about 100 tugs on order worldwide.

Design information on tugs and towboats is presented in Chapter 47.

3.2.5.4 Other types of oceangoing vessels

The principal types of seagoing vessels not addressed in the preceding sections and sub-sections are dredgers, research vessels, icebreakers, and cable ships.

At the beginning of 2003, there were 1126 self-propelled *dredgers* in the world fleet. The vessels in this fleet vary considerably in size. There are essentially two dredger fleets; the larger vessels being designed to store and to transport the dredge spoil, while the smaller ones are designed only to dredge, with the dredge spoil being transferred by barge, pipeline, or other means. Self-propelled dredgers average around 1800 gross tons in size and have an average age pf about 21 years, which is rising; in 2001, however, the renewal rate was a healthy 3.8%.

The operation of dredgers is a requirement of every country with a deep water port or a river shipping system and this is reflected in the broad international distribution of their ownership. The importance of dredging to the efficient operation of ports is reflected also in the heavy concentration of their ownership among governmental bodies, particularly including port authorities.

The geographic distribution of the ownership of the dredger fleet is consistent with this logic. By far the largest concentration of dredgers is in the Netherlands, and in Japan, each of which has close to 20% of the world fleet. This reflects the extent to which these land-poor countries have created land from the sea through dredging. Other countries with large fleets of dredgers are China, Belgium, and Britain.

The construction of dredgers follows their ownership, the leading builders being concentrated in Japan and the Netherlands.

At the beginning of 2002, there were 857 *research vessels* in the world fleet. The vessels in this fleet vary considerably in size, there being essentially two research vessel fleets, the larger vessels being Government-owned and designed for worldwide service, while the smaller ones are privately owned and generally designed with only limited operations in mind. Research vessels average about 1500 gross tons in size and have an average age of about 23 years, which is rising rapidly. In 2001, the renewal rate was only 1.5%.

The operation of research vessels is a characteristic of virtually every country with a significant deep water economic zone, a significant fishing industry, or a significant offshore oil and gas industry. These characteristics are reflected in the international distribution of their ownership. The importance attached to ocean research is also reflected in the heavy concentration of ownership of this type of vessel among governmental agencies and academic institutions.

The geographic distribution of the ownership of the research vessel fleet is consistent with this logic. By far the largest concentration of research vessels is in Russia, which has 142, and in the U.S., which has 133. Other countries with relatively large fleets of research vessels are Norway with 57, and China with 56.

The construction of research vessels follows their ownership, the leading builders being concentrated in the U.S. and Russia.

There are about 100 *icebreakers* in the world fleet. Icebreakers do not vary much in size, averaging about 6000 gross tons. The average age is about 25 years.

The operation of icebreakers is necessarily a requirement of countries with coasts and rivers adjoining the Arctic or at least experiencing Arctic weather, the solitary Antarctic application being in Argentina.

The geographic distribution of the ownership of the icebreaker fleet is consistent with this logic. The largest concentrations of icebreakers are in Russia, which has 28, and Canada, which has 18. Ownership is heavily concentrated in national governments.

The construction of icebreakers is dominated by Finnish shipyards, which have historically built almost all the icebreakers in the Russian fleet. Additional expertise is found in Canada.

There are about 60 *cable ships* in the world fleet. The vessels in this fleet do not vary much in size, averaging about 4300 gross tons; their average age is about 21 years.

The operation of cable ships is a requirement of a developed country, for which reliable intercontinental communication is a critical factor in the conduct of its international politics and business. While it appeared possible for a time that satellite communications might make undersea cables redundant, the developed countries of the world have continued to maintain ocean cable connections and even to develop new ones for fiber-optic cables.

The geographic distribution of the ownership of the cable ship fleet is consistent with this logic. By far the largest concentrations of cable ships are in Britain which has 11, Norway which has 8, Japan which has 6, and the U.S. which has 6. Ownership is mostly held either by national governments or by the larger telecommunications companies.

Finnish shipyards have dominated the construction of cable ships in recent years, but there is additional expertise to be found in shipyards worldwide and several Far East shipyards have recently begun to target this sector.

In addition to the various ship types discussed in this section, there are about 2824 seagoing ships of unspecified type in the world fleet. This group averages only about 1100 gross tons in size and its average age is 21 years. It consists predominantly of vessels used in coastal and harbor service, such as buoy tenders, passenger tenders, disposal vessels for dredge spoil and sewage sludge, and crane ships. It probably also includes some commercial vessels that have been converted to quasi-military uses.

The ownership of these miscellaneous vessels is concentrated in countries with extensive coastlines and large numbers of developed ports, particularly Japan (420), the U.S. (238), and Russia (212).

Design informing for the vessels covered in this subsection is presented as follows:

Chapter 40 - Ice Capable Ships
Chapter 50 - Dredgers
Chapter 53 - Oceanographic Ships

3.2.6 Barges and Other Inshore Vessels

The world fleet of barges consists primarily of cargo-carrying vessels, although there is a small number of other types, such as are used in marine construction or as floating accommodation. The U.S. fleet in this category is fairly well defined. In Western Europe it is less well defined and in the former Soviet Union it is much less well defined. Elsewhere, sources of data are few and unreliable. As a result, the discussion in this section is confined to the barge and inland operations of the U.S, Western Europe and the former Soviet Union.

Other inshore vessels include inshore fishing vessels, small ferries, passenger vessels used by the tourism industry, small tugboats, and many other categories of small craft for which insufficient space is available here for an adequate discussion. In the U.S. alone there are over 55 000 craft in these categories on record by the USCG.

Also not addressed here, for reasons of space, is the pleasure craft industry. The USCG estimates that there are over 75 million pleasure craft of different types and sizes in the U.S. and there must, therefore, be at least three to four times that figure in the rest of the world.

Table 3.IX summarizes the world fleet of barges and other inshore vessels. The figures in the right-hand column of this table are purely speculative.

TABLE 3.IX The World Fleet of Barges and Other Inshore Vessels

Ship Type Category	*U.S.*	*Other*
Oceangoing Cargo Barges	2500	500+
Non-Oceangoing Cargo Barges	25 000	45 000+
Other Inshore Vessels	55 000	110 000+
Total	**82 500**	**155 500+**

3.2.6.1 Oceangoing cargo barges

There are about 2500 oceangoing cargo barges in the U.S. as registered by the USCG, most of them tank barges employed in the distribution of refined products along the U.S. coast line. The remainder includes small numbers of dry bulk cargo barges, multi-deck trailer barges, container barges and deck cargo barges.

Oceangoing barges are popular in the U.S. because U.S. laws make them much more economical to operate than self-propelled ships of the same capacity. This is not the case anywhere else in the world and the number of oceangoing barges outside the U.S. is negligible. The only country in which oceangoing barges are used in any number is Japan, where geography makes them economically advantageous.

3.2.6.2 Non-oceangoing cargo barges

The USCG records show that there are about 25 000 non-oceangoing cargo barges in the U.S., almost all of them employed on the Mississippi River system. The largest type is the hopper barge, of which there are about 22 000, followed by the tank barge fleet, of which there are about 3000. Almost all these inland barges are 60 meters long by 10.7 meters wide.

Non-oceangoing barges are popular in the U.S. because of the topography of the Mississippi River system. Other regions have similar river systems and also have inland shipping systems. Most other inland shipping systems, however, have developed very differently from that of the U.S., with emphasis on the use of specially designed, self-propelled river-trading ships. The principal system in Western Europe is based on the Rhine River, although there is also cargo shipping on a smaller scale on the Rhone River and on the Danube River, while the principal system in Eastern Europe is based on the Volga River, with cargo shipping on a smaller scale on the Don and the Amur Rivers (19).

There are about 16 000 vessels on the Rhine River system and on the lesser systems of Western Europe. They range in size from the traditional Rhine barge, which is rarely larger than 500 deadweight tonnes and is now a dying breed, to modern self-propelled river/ocean traders, which are usually of either 1000 or 2200 deadweight tonnes. These newer vessels have 900 kW power and do about 11 knots when loaded. The fleet is growing fast as trading into the Baltic and the North Sea becomes increasingly attractive and with the opening up of connections to the Danube River, which provide the potential for trading into the Black Sea.

There are about 4000 vessels on the Danube River system. They are somewhat larger than on the Rhine River system, the average being about 3000 deadweight tonnes. Trade has suffered in recent years from the effects of political and economic crises in the region and the fleet is not growing.

There are also about 25 000 vessels on the Volga River system, although how many of these are actually operating is not clear. Almost all are of mass-produced designs,· the largest of which is about 3000 deadweight tonnes. They include general-cargo ships, tankers, a combination type that carries liquid cargo down bound and dry cargo upbound, and the remainder is of miscellaneous types.

3.2.6.3 Other Inshore Vessels

The USCG records show that the other inshore and non-self-propelled vessels in the U.S. inventory include about 25 000 small commercial fishing vessels, about 5000 small tugs and towboats, about 10 000 small passenger vessels and about 15000 small vessels of miscellaneous types.

The number of other inshore and non-self-propelled vessels outside the U.S. is hard to assess. In general, if the economies of the other OECD nations are collectively about twice the size of the U.S. economy, it may be reasonable to expect them to support an inventory of comparable proportions.

Design information for lake and inland vessels is presented in Chapter 39.

3.3 THE MARINE INDUSTRY TODAY

3.3.1 INTRODUCTION

The structure ofthe international marine industry today can be defined in five categories. The first three of these five industry sectors are those that are primarily concerned with ship design and construction, but no discussion of the structure of the international marine industry would be complete without some consideration of the other two:

1. *ship design-including* firms of consulting naval architects, university schools of naval architecture and classification societies,
2. *ship construction-the* shipbuilding industry itself, including not only the relatively small number of very large shipbuilders but also the much larger universe of smaller shipbuilders,
3. *marine manufacturing-those* companies that manufacture the machinery, equipment and outfit that is installed in ships.
4. *ship operation-the* increasingly complex sector of the industry that is concerned with the day-to-day operation of ships, and
5. *ship repair-those* shipyards that concentrate on the maintenance and repair of ships and that have dry-docking capabilities.

These five industries are supported by numerous smaller industries, not addressed here, that are primarily subsets of other industries, such as maritime and admiralty lawyers, marine insurance brokers; ship brokers; shipping agents; ship chandlers and bunkering companies; port authorities, terminal operators and stevedores; pilots, marine surveyors and other providers of technical services, and finally, of course, ship breakers.

Table 3.x summarizes the structure of the international marine industry in terms of numbers of companies or organizations and numbers of employees. These figures are very approximate but they provide an indication of the major role that the marine industry plays in the world economy.

3.3.2 Ship Design

The design of ships is the profession of naval architecture. Other disciplines are involved, particularly that of marine engineering, but the fundamental responsibility belongs to the naval architect.

Naval architects and marine engineers work in all sectors of the marine industry, including those discussed in the following sub-sections, but there are three types of establishment where significant numbers of them are employed and where they are primarily concerned with the design of ships (20) (see Chapter 5 - Ship Design Process, and Chapter 11 - Parametric Design, and the individual 'ship type design chapters in Volume II).

3.3.2.1 Naval architectural firms

There are at least 250 naval architectural firms worldwide, as shown in Table 3.xI. These figures are very approximate, for the following reasons.

Outside the U.S., most new ships are designed either by their prospective owners or by their builders. As a result, most firms of consulting naval architects are quite small, concentrating on the provision of specialized services to shipowners, operators and builders, both in the private and in the public sector, that have limited internal capabilities.

In the U.S., the reverse was true until fairly recently. Most ships were designed by a naval architect working under contract to the prospective shipowner, but a few shipowners or shipyards developed original designs. In recent years, however, an increasing volume of design work has been done by shipowners and shipbuilders, and more designs have been acquired by license from European or Asian sources.

At the same time, technological advances have made the exchange of data so simple that there has been a proliferation of smaller naval architectural firms, including many sole practitioners who work at home, and even the smallest shipbuilders and shipowners have found it possible to obtain access to designs and other technical information from all over the world. Of the roughly 125 companies in North America that describe themselves as consulting naval architects, only six provide the complete range of serviees, from concept design through detailed work packages for use in the shipyard.

This trend is now being seen elsewhere. The number of naval architectural firms in Western Europe has ballooned in recent years, as the indigenous shipbuilding industry has declined and shipyard engineering departments have reconstituted themselves as consulting companies. Similarly, there is an increasing number of naval architectural firms in Asia, and Australasia: the figure shown in Table 3.x almost certainly understates the true state of affairs in that regIOn.

It should be noted here that the difficulty of counting naval architectural firms is exacerbated by several additional factors. For example, many firms that provide naval architectural services also provide other types of marine consulting services, such as marine surveying and industrial consulting. There are, in addition, hundreds of small firms worldwide that are active in these areas but do not design ships. There are also hundreds of individuals-naval architects, engineers of many disciplines, retired shipbuilders, retired merchant mariners, a host of retired government employees, both uniformed and civilian, and others-who offer various types oftechnical services as independent marine consultants.

There are only a few large naval architectural firms: most have fewer than 25 employees. Allowing for the large number of single practitioners, the number of people earning a living in this sector is probably in a range between 5000 and 10 000.

TABLE 3.X Marine Companies and Employment

Industry Sector	*Companies/ Organizations*		*Employment*	
	Min.	*Max.*	*Min.*	*Max.*
Ship Design	350	450	25 000	35 000
Shipbuilding	450	500	335 000	400 000
Manufacturing	800	1000	500 000	800 000
Ship Operation	2000	3000	1 750 000	2 250 000
Navies	400	450	2 500 000	2 750 000
Ship Repair	500	600	100 000	120 000
Total	**4500**	**6000**	**5 200 000**	**6 355 000**

3.3.2.2 Universities

Most countries that have a maritime industry have at least one university that offers bachelor's and/or master's degree courses in naval architecture, Britain, Japan and the U.S. have several. There are about 65 universities worldwide as shown on Table 3.xII.

The teaching of naval architecture has been a growth area in recent decades. Prior to World War II, this table would have counted only about a dozen institutions worldwide. The growth and increased geographic dispersion of the international shipping and shipbuilding industries since World War II have created an increased demand for naval architects and hence for schools of naval architecture. In addition, the university business itself has grown exponentially, with many small and local colleges increasing the scope ofthe courses that they offer, and this growth has itself fed the demand.

It should also be noted here that, in addition to schools that offer bachelor's courses and/or graduate degrees in naval architecture, designed for students who plan either to practice as naval architects or to enter shipyard management, there are many other establishments that teach naval architecture and/or marine engineering as an adjunct to related studies. Prominent among these are those focused on the training of ships' officers-naval academies, merchant marine academies and cadet training schools-but they also include not only schools with ocean engineering departments, but also many junior colleges and vocational training schools that are located in areas with marine industry activity.

Universities are not large employers of naval architects; the number of people earning a living in this sector is not likely to be more than about 1000.

3.3.2.3 Classification societies

There are 23 classification societies worldwide that are actively engaged in ryviewing and approving the design and construction of ships, as shown on Table 3.XIII. Of this number, 12 societies are members or associate members of the International Association of Classification Societies, (lACS), which classifies over 90% of the world fleet measured by GT, and more than 60% measured by number of ships (21).

The major classification societies are also major employers. The largest, Lloyd's Register of Shipping, has about 6000 employees and even the smallest have several hundred. Based on the figures provided by those societies which publish them, the number of people earning a living in this sector is in a range between 20 000 and 25 000.

A discussion of this topic is provided in Chapter 8 - Regulatory and Classification Requirements.

3.3.3 Ship Construction

At the beginning of 2003, there were about 540 shipyards worldwide actively building ships for commercial or governmental, that is, non-recreational clients (22). These shipyards can be divided into three categories that reflect not

TABLE 3.XI Naval Architectural Firms

Region	*Number*
North America	125
Western Europe	85
Eastern Europe	10
Asia and Australasia	15
Other	15
Total	250

TABLE 3.XII Universities Offering Degree Courses in Naval Architecture

Region	*Number*
North America	8
South America	3
Western Europe	25
Eastern Europe	8
Asia and Australasia	20
Total	65

TABLE 3.XIII Classification Societies

	Number	
Region	*lACS*	*Other*
North America	1	0
Western Europe	6	4
Eastern Europe	1	3
Asia! Australasia	4	2
Other	0	2
Total	12	11

only their size, but also the scale of their investment in the facilities required to be a serious international competitor:

- *major shipyards-those* that build ships that are larger than Panamax in breadth,
- *medium-sized shipyards-those* that build oceangoing ships of Panamax or less, and
- *small shipyards-those* that only build small oceangoing and non-oceangoing ships and barges.

Shipbuilding is still a fairly labor-intensive industry and shipbuilders are major employers, although an increasing proportion of the industry's workforce is now employed by subcontractors rather than by the shipbuilders themselves.

About 335 000 people earn a living in shipbuilding, about 30% ofthem in the U.S., which, despite its low ranking in the output tables, has the largest shipbuilding industry in the world measured in terms of employment, the largest being that of China (23).

3.3.3.1 Major shipyards

At the beginning of2003, 39 shipyards, in 13 different countries, were actively building ships that were larger than Panamax in breadth. Of these 39 shipyards, 17 were in Japan. The distribution is shown in Table 3,XIV.

It should be noted that all these companies also built medium-sized ships.

It is also noteworthy that 16 of the 39 shipyards are owned by very large multinational corporations, for which shipbuilding is only one of many activities. Eleven, in China, Croatia, Italy, Romania, Spain, and Taiwan are state-owned, and three, all in the U.S., are owned by large, publicly traded defense contractors. Only one shipyard outside Japan is owned by a privately held company-Odense Steel Shipyard in Denmark.

3.3.3.2 Medium-sized shipyards

In the beginning of 2003, 76 medium-sized shipyards, in 18 countries, were actively building oceangoing cargo ships and naval vessels of Panamax breadth or less. These totals do not include any of the major shipyards listed in the previous subsection, all of which also build medium-sized ships. The regional distribution is shown in Table 3,XV.

The leading nations in the construction of medium-sized ships were China with 18 yards, followed by Japan with 16 yards, Germany with 9, and the U.S. with 6. The remaining 27 yards are spread over 14 different countries.

3.3.3.3 Small shipyards

It is very difficult to count small shipyards. The facilities required to build small ships, barges and other craft are much less capital-intensive than those of the major shipyards and the markets in which s~all shipyards operate tend to be not only domestic but also localized. As a result, small shipyards open and close with frequency. In addition, their activities are not as widely reported as are those of their bigger cousins.

Table 3,XVI summarizes the inventory of small shipyards as best it can be counted at the beginning of 2003.

TABLE 3.XIV Major Shipyards

Region	*Countries*	*Yards*
North America	1	3
South America	1	1
Western Europe	6	9
Eastern Europe	1	1
Asia	4	25
World Total	13	39

TABLE 3.XV Medium-sized Shipyards

Region	*Countries*	*Yards*
North America	1	6
Western Europe	8	23
Eastern Europe	4	7
Asia	5	40
World Total	18	76

TABLE 3.XVI Small Shipyards

Region	*Countries*	*Yards*
North America	2	36
South America	5	13
Western Europe	14	144
Eastern Europe	8	37
Africa	2	10
Australasia	1	10
Asia	11	110
World Total	43	340

The companies included in this summary all build ships, large barges and other commercial craft, of less than about 10 000 tons and primarily employed in coastal, inshore and inland activities. In addition, this summary includes those shipyards that have been consistently in the business of building ships for an extended period, and does not include those for which shipbuilding is only an occasional activity. The leading nations in terms of small-ship shipbuilding are Japan, which has about 38 small shipyards, followed by China and the U.S., each with 32, the Netherlands, with 28, Norway, with 27 and Spain, with 21. The remaining 169 are spread over 41 countries.

3.3.4 Marine Manufacturing

Shipbuilding is an assembly industry. The art of shipbuilding lies in the ability to buy a wide variety of semi-processed and fully manufactured material and equipment from other companies and to combine them efficiently into a finished ship.

The value of the material and equipment that a shipbuilder buys is, in fact, much greater than the value added in the shipbuilding process, although the actual proportions vary from country to country and with different sizes and types of ship.

As a result, there are many times more marine manufacturers than there are shipbuilders. In addition, relatively few marine manufacturers confine their business activities to marine markets and any tabulation of marine manufacturers inevitably becomes increasingly non-marine.

In this sub-section, therefore, a brief review of the major manufacturers of uniquely marine components is all that is realistically possible. The principal categories are propulsion machinery, propulsors, cargo-handling systems, steering and mooring systems, and navigation systems (24).

The difficulty of defining precisely the structure of the marine manufacturing industry also applies to the problem of counting its workforce. In general, if the labor-material split in shipbuilding is in the region of 40-60, it is not unreasonable to suppose that the marine manufacturing industry employs 1.5 times the number of people that the shipbuilding industry employs. This would mean that the number of companies in the industry is at least 800, and second, that the number of people earning a living in marine manufacturing is in the region of 500 000.

3.3.4.1 Propulsion machinery manufacturers

The single most expensive item that shipbuilders buy is usually the ship's main propulsion engine. This is almost universally a diesel engine, although there are small numbers of ships that are powered by either steam turbines or by gas turbines.

Marine diesel engines are categorized as slow-speed, medium-speed or high-speed, depending on their speed in rpm:

1. *slow-speed diesels* have speeds from about 75 to about 200 rpm and develop powers from about 700 to about 6000 kW per cylinder. They require no gearbox and are the preferred machinery on almost all large cargo ships. As a result of mergers and acquisitions during the 1970s and 1980s, there are now only three builders of slow-speed diesels, although the size of these engines requires each to have licensees worldwide. Many of these licensees, such as Hyundai, now produce many more engines every year than do the original designers/manufacturers.
2. *medium-speed diesels* have speeds from about 500 to about 1000 rpm and develop powers from about 100 to

TABLE 3.XVII Propulsion Machinery Manufacturers

Typical Products	*Major Manufacturers*
Slow-Speed Diesel	M.A.N./B&W
	Mitsubishi
	Wartsila
Medium-Speed Diesel	M.A.N./B&W
	Niigata
	Pielstick
	Wartsila
High-Speed Diesel	Alstom
	Bergen Diesel
	Caterpillar
	Cummins
	Daihatsu
	Detroit Diesel
	Deutz
	MaK
	M.A.N.
	MWM
	MTU
	Wichmann
	Yanmar
Steam Turbine	Alsthom
	General Electric
Gas Turbine	General Electric
	Pratt & Whitney
	Rolls-Royce
	Zorya

about 1000 kW per cylinder. They require a gearbox and are the preferred equipment on smaller cargo ships, on naval ships and on passenger ships. There has been rationalization in this sector also, and there are now only five major manufacturers of medium-speed diesels.

3. *high-speed diesels* have speeds from about 1000 to about 3000 rpm and develop powers from about 40 to about 400 kW per cylinder. They require a gearbox and are the preferred equipment on all small ships and craft. This sector has been more stable than the other two and there are still about 12 major manufacturers of high-speed diesels. A high-speed diesel being not too different from a large truck engine, this sector is dominated by large companies that are better known in other industries.

Steam turbines are used less and less, as diesel technology allows the construction of ever-larger slow-speed engines. There are three groups of ships which are still operated by steam turbines: very large tankers built prior to about 1990, LNG carriers, although even these are changing to slow speed diesels, and nuclear-powered warships.

As steam turbines have become increasingly rare, gas turbines have become more common, but their application has so far been largely limited to warships. The gas turbine manufacturers are, however, beginning to penetrate the market for high-speed vessel types and cruise ships.

The major manufacturers of propulsion machinery are listed in Table 3.XVII.

3.3.4.2 Propulsor manufacturers

Marine propellers are mostly manufactured by companies that are specialists. There has been considerable rationalization in this industry in recent years and there are now fewer than 20 major manufacturers worldwide: they are concentrated, as might be expected,· in the regions where ship construction is concentrated.

In addition, there has been considerable growth in recent years not only in the use of azimuthing and other types of steerable propulsors, but also in podded, external propulsion systems.

The major manufacturers of propellers and thrusters are shown in Table 3.xVIII.

3.3.4.3 Cargo handling system manufacturers

Cargo handling systems take different forms: tankers require cargo pumping systems, bulkers require grab cranes, conveyors or vacuum systems, general cargo ships require cranes, sliding doors, hatch covers and ramps. Most of these systems are made by companies that are specialists in the field.

Since much of the technology in this field originated in Europe, the major manufacturing companies are also concentrated in this region. Many of these companies are noW primarily engaged in design work; the manufacturing itsdf is distributed worldwide, by means of subcontracting and similar technology agreements, as the developers of the various technologies take advantage of lower manufacturing costs in less developed countries.

The major manufacturers of shipboard cargo handling systems are shown in Table 3.xIX.

3.3.4.4 Steering and mooring system manufacturers

Steering gear and mooring systems are almost all manufactured by companies that are specialists in the field. As with cargo systems, these manufacturing companies are

TABLE 3.XVIII Propeller and Thruster Manufacturers

Typical Products	*Major Manufacturers*
Propellers	Nakashima Rolls-Royce Wartsila
Propulsors and Thrusters	ABB Drives Aquamaster Brunvoll Hamilton Jet Nakashima Omnithruster Rolls-Royce Schottel Voith Hydro Wartsila

TABLE 3.XIX Cargo Handling System Manufacturers

Typical Products	*Major Manufacturers*
Liquid Cargo Systems	Framo Pumps Hamworthy KSE Svanehoj
Dry Bulk Cargo Systems	InterSystems Seabulk Systems
Cranes, Ramps and Other General Cargo Systems	Hagglunds Hamworthy KSE Liebherr McGregor Tsuji

TABLE 3.XX Steering/Mooring System Manufacturers

Typical Products	*Major Manufacturers*
Steering Gear	Hatlapa Jastram Rolls-Royce
Mooring Equipment	Clarke Chapman Hatlapa Hydralift Rolls-Royce

TABLE 3.XXI Navigation System Manufacturers

Typical Products	*Major Manufacturers*
Integrated Bridge Systems, Collision Avoidance Systems, Alarm and Control Systems, Communications Systems, etc.	Alstom, Kongsberg, Cegelec, Furuno, Norcontrol, Radio-Holland, Raytheon Marine, Simrad, Sperry Marine

heavily concentrated in Northwest Europe and Japan. The major manufacturers are shown in Table 3.xX.

3.3.4.5 Navigation system manufacturers

Navigation systems are almost all manufactured by companies that are specialists in the field. These companies are heavily concentrated in Northwest Europe, North America and Japan.

The major manufacturers are shown in Table 3.xXI.

3.3.5 Ship Operation

In early 2003, there were over 40 000 shipowners and operators worldwide actively operating ships (25). This figure is misleading, however, because many shipping companies are legally structured to be responsible for a limited number of ships, just as most ships are owned by corporations established only for that purpose. However, economies of scale apply in shipping as elsewhere, and one operator will generally be responsible for many ships, even though it may use several different names and operate ships for many different owners (26).

Ship operating companies can be divided into six categories that reflect not only their size as companies but also their involvement in the industry:

1. navies and other governmental agencies,
2. government-owned ship operators,
3. major multinational corporations,
4. independent ship operators,
5. owner-operators, and
6. ship managers.

A world fleet of about 47 000 commercial cargo and passenger ships must support 550 000 to 700 000 seagoing billets. If each billet requires, on average, 1.5 seamen, the seagoing workforce must be in a range from 825 000 to 1 050000. Allowing for shore staff, the total must be somewhere between 1 000 000 and 1 250 000.

There are close to 100 000 other commercial vessels of various types in the world fleet, including both the oce'angoing and the inshore categories. These vessels, being generally very small, provide fewer crew billets and employ fewer seamen per billet. A conservative estimate for t;mployment in this sector is 750 000 to 1 000000 jobs.

Finally, there are about 400 navies, coast guards and other government agencies, operating about 26 500 vessels and employing over 2 000 000 uniformed personnel (27). The U.S. Navy employs about 1 civilian for every 2 uniformed personnel, but most other navies manage with much lower ratios: the number of civilian employees in the world's navies could nevertheless be over 500 000.

3.3.5.1 Navies and other governmental agencies

Every nation with a coastline or with a national boundary that runs across a lake or along a river has a navy of some kind. It may be very small and it may not be called a navy, but it involves vessels that are owned by the national government, that are armed, if only by small arms, and that are crewed by uniformed personnel. There are 181 such nations in the world.

If a major navy can be categorized as one that operates at least one large surface combatant or submarine, there are 58 major navies. The number of truly large navies, those with aircraft carriers and sufficient strength to operate credibly outside their immediate geographic area, is still only five, the U.S., Russia, China, Britain and France, but several 2nd-tier nations now have considerable fleets, notably Turkey, which now has the third largest navy in Europe, Italy, India, Indonesia, Japan and South Korea.

The structure of the world's navies is shown in Table 3.xXII.

3.3.5.2 Government-owned ship operators

The principal reason for a national Government to own and operate commercial ships is to control the transportation of the country's critical commodities: for developed nations,

TABLE 3.XXII Navies and Other Military Forces

Region	*Category*	*#*	*Uniformed Personnel*	*Large Combt.*	*Other Vessels*	*Total Fleet*
N. America	Major	2	594 591	244	5239	5483
	Minor	0	0	0	0	0
	Total	2	594 591	244	5239	5483
C. America/Caribbean	Major	2	39 500	8	324	332
	Minor	26	10 248	0	393	393
	Total	28	49 748	8	717	725
S. America	Major	8	154 490	92	1449	1541
	Minor	5	9160	0	125	125
	Total	13	163 650	92	1574	1666
W. Europe	Major	13	322 890	351	5585	5936
	Minor	14	9766	0	285	285
	Total	27	332 656	351	5870	6221
E. Europe	Major	6	227 480	167	2572	2739
	Minor	12	12 560	0	256	256
	Total	18	240 040	167	2828	2995
Middle East	Major	5	46 200	19	627	646
	Minor	8	15 470	0	334	334
	Total	13	61 670	19	961	980
S./SE. Asia	Major	9	184 000	118	2671	2789
	Minor	5	44 419	0	488	488
	Total	14	228 419	118	3159	3277
Far East	Major	5	297 300	367	3420	3787
	Minor	1	2600	0	94	94
	Total	6	299 900	367	3514	3881
Australasia/Oceania	Major	2	15 572	26	348	374
	Minor	12	1272	0	37	37
	Total	14	16 844	26	385	411
Africa	Major	6	47 187	37	438	475
	Minor	40	19 118	0	360	360
	Total	46	66 305	37	798	835
Total World	*Major*	*58*	*1 929 210*	*1429*	*22 673*	*24 102*
	Minor	*123*	*124 613*	*0*	*2372*	*2372*
	Grand Total	**181**	**2 053 823**	**1429**	**25 045**	**26 474**

this should mean critical imports, while for developing nations, it is more likely to mean critical exports. The best examples are the oil and gas producing nations. For the U.S., critical commodities are defense materials. A secondary reason is the prestige associated with the maintenance of a shipping company flying the national flag around the world, comparable to the maintenance of a national-flag airline: this is much less common today than it was 20 or 30 years ago, especially with the current worldwide trend to privatization of state-owned companies.

There are now few government-owned shipping companies of any significance, as shown on Table 3.xXIII.

3.3.5.3 Major multinational corporations

Multinational corporations whose operations require the availability of large quantities of ocean shipping capacity understandably seek to protect themselves from the uncertainties of the market-place by controlling as much of their requirements as they think necessary. This usually takes the form of direct ownership of half or more of their requirements, although much less for oil companies, long-term chartering of some part of the balance and short-term chartering of the remainder.

There are now fewer than 20 such companies worldwide with significant fleets, as shown in Table 3.xXIV.

This category includes companies that are directly involved in the production or consumption of natural resources such as crude oil, agricultural products and mining products. There used to be more large tanker fleets operated by major oil companies, but the oil majors have in recent years turned over their shipping operations to ship management companies in order to distance themselves from the liabilities associated with oil spill clean-up legislation and litigation, particularly in the U.S.

Also included are some of the major international trading companies with worldwide shipping and trading activities, although there are not as many of these as one might expect.

3.3.5.4 Independent ship operators

The history of the international shipping industry is revealed in the number of large independent ship operating companies. These companies are almost exclusively based in countries that have been actively involved in ocean shipping not just for decades but for centuries, such as Britain, Norway, and Greece.

With the sale of Sea-Land to Maersk, of American President Lines to Neptune Orient Line, of Lykes Line to CP Ships, and of Farrell Lines to P&O/NedLloyd, the U.S. now has only one independent liner operator in foreign trade.

Some of the major independent ship operators are shown in Table 3.xXV.

TABLE 3.XXIII Government-owned Ship Operators

Region	*Major Operators*
North America	Military Sealift Command (US)
South America	CSAV (Chile) Docemar (Brazil) PDVSA (Venezuela)
Western Europe	None
Eastern Europe	None
Africa	None
Middle East	Abu Dhabi National Tanker Co. Iranian Islamic Rep. Shipping Co. National Iranian Tanker Co. Kuwait Oil Tanker Co. United Arab Shipping Co. Saudi Arabian Nat'l. Shipping Co.
Asia	China Ocean Shipping Co. Petronas (Indonesia) Malaysian Int'l. Shipping Co.

TABLE 3.XXIV Major Multinational Shipping Companies

Type of Company	*Major Companies*
Oil Companies	BP Chevron Texaco Exxon Mobil Shell
Agricultural Commodities	Louis-Dreyfus
Mined Products	BHP Corus Krupp
Trading Companies	Hanjin Hyundai Kawasaki Mitsubishi Mitsui

3.3.5.5 Owner-operators

Most operators of smaller ships, including fishing vessels and many offshore supply vessels, are owner-operators. This category also includes many small cargo ship operators, especially those engaged in coastal and other short-sea trad-

TABLE 3.XXV Major Independent Ship Operators

Region	*Major Companies*
Western Europe	Bergesen (Norway) A.P. Moller (Denmark) Wilhelmsen (Norway) P&O NedLloyd (UK/Neth.)
Asia	OOCL (Hong Kong) K Line (Japan) Mitsui Overseas Line (Japan) NYK Line (Japan) Korea Line (Korea) Neptune Orient (Singapore) Evergreen (Taiwan)

ing. Notable in this category are the numerous small containership, break-bulk cargo ship, and tanker operators still to be found in northwest Europe and the Baltic.

There are many more such companies worldwide: they are concentrated, as might be expected, not only in the regions where shipping activity is greatest, but also in regions where coastal, inter-island and feeder services are required.

3.3.5.6 Ship managers

Professional ship managers are a relatively new feature of the international shipping scene. The use of ship managers has grown considerably as some owners have tried to distance themselves from the risks and liabilities of ship operations, particularly in the oil industry. Other owners simply seek the economies of scale achievable through the use of a contract operator.

Many ship managers started out as independent shipping companies, while others were created for this purpose. The business is dominated by British companies, because of the availability of expertise resulting from the decline in the British fleet, but there are several other nationalities involved in the industry.

There are now about 1200 ship management companies worldwide, although many are regional subsidiaries oflarge companies and many others only manage one or two ships. Ship managers are concentrated, as might be expected, in those countries which encourage them, primarily Britain, Cyprus, Germany, Greece, Hong Kong, India, the Netherlands, Norway, the Philippines, Russia, Singapore, Ukraine, and the U.S.

The geographic distribution of ship management companies is shown on Table 3.xXVI and the major companies are listed on Table 3.xXVII (28).

TABLE 3.XXVI Geographic Distribution of Ship Managers

Country	*Number*
North America	93
Central/South America	48
Western Europe	484
Eastern Europe	183
Africa	19
Middle East	38
Australasia	24
Asia	309
World Total	**1198**

TABLE 3.XXVII Major International Ship Managers

Country	*Major Companies*
Norway	Barber Ship Mgmt.
Cyprus	Columbia Ship Mgmt. Seatankers
Monaco	V Ships
Hong Kong	Wallem Ship Mgmt.
Switzerland	Acomarit Ship Mgmt.
U.K.	Northern Ship Mgmt.

3.3.5.7 Ship registries

The concept of a *flag of convenience* was first developed by U.S. shipowners seeking relief from the high costs of U.S. flag shipping as well as from U.S. tax laws. The original flags of convenience were those of Panama, Liberia, and Honduras. Other countries have been attracted to the business by the success of Panama and Liberia and by the prestige and international exposure that a flag is presumed to bring.

At the same time, the shift in economic advantage in the international shipping industry from the developed countries of Europe to the less developed countries of Asia forced many European shipping companies to seek alternative flags.

Switching a national flag fleet to a flag of convenience

TABLE 3.XXVIII Second Registries

First Registry	*Second Registry*
Belgium	Luxembourg
Britain	Bermuda, Cayman Islands, Isle of Man
Denmark	Danish Int'l. Register (DIS)
France	French Antarctic Territory
Netherlands	Netherlands Antilles
Norway	Norwegian Int'l. Register (NIS)
Portugal	Madeira
Spain	Canary Islands
U.S.	Marshall Islands

TABLE 3.XXIX Flags of Convenience

Registry	*Type*	*GT (mm)*
Panama	FOC	122.4
Liberia	FOC	51.8
Bahamas	FOC	33.4
Malta	FOC	27.1
Cyprus	FOC	22.8
NIS	2nd Registry	19.0
Marshall Islands	2nd Registry	11.7
Saint Vincent	FOC	7.1
DIS	2nd Registry	6.6
Isle of Man	2nd Registry	6.1
Philippines	FOC	6.0
Bermuda	FOC	5.3
Antigua	FOC	4.7
French Antarctic	2nd Registry	3.1
Cayman Islands	2nd Registry	2.1
Belize	FOC	1.8
Canary Islands	2nd Registry	1.6
Vanuatu	FOC	1.5
Luxembourg	2nd Registry	1.5
Neth. Antilles	2nd Registry	1.2
Honduras	FOC	1.0

can create political problems, however, and many shipowners sought a flag with the right political connections, such as that of a former colony or overseas territory, giving rise to a second tier of alternative flags, the so-called second registries. Where a former colony was not available, an international registry was created by law to provide the equivalent benefits.

The principal second registries are listed in Table 3.xXVIII. The leading flags of convenience are listed in Table 3.xXIX ranked by size of fleet. This table includes the second registries, in order to show their sizes (29).

3.3.6 Ship Repair

At the beginning of 2003, there were about 2400 drydocks available worldwide for the repair of ships belonging to commercial or governmental, that is non-recreational, clients (30). These drydocks can be divided into four size categories, as follows:

1. very large-those dry docks that are designed to accommodate ships of "post-Panamax" breadth; these have a length of at least 215 meters and a clear breadth between wing-walls of at least 40 meters,
2. large-those drydocks that are designed to accommodate ships of Panamax breadth; these have a length of at least 185 meters and a clear breadth between wing-walls of at least 32 meters but not more than 40 meters,
3. small-those drydocks that are not large enough to accommodate ships of Panamax breadth but can lift most other ocean going vessels; these have a clear width between wing-walls of at least 20 meters but not more than 32 meters, and
4. very small-those drydocks that are not large enough to accommodate ships with a breadth greater than 20 meters.

The term drydock is used in this section in its generic sense, as a facility that is designed to allow work on the underwater portion of a ship: drydocks include graving docks, floating docks, ship lifts, marine railways, and slipways.

Employment in the ship repair industry is difficult to define precisely, because so much repair work is now performed by companies outside the structure of the industry. Based on one reliable source, that portion of the industry that is concerned with ships of over 10 000 DWT has total revenues of around $6 billion and employs about 85 000 people. This estimate covers about 14000 vessels, totaling close to 500 million GT: average expenditure is, therefore, about $450 000 per ship, or about $12 per GT. If $12 per GT is also valid for the remaining 70 000 vessels in the world fleet, which total only another 45 million GT, total repair industry revenues should be in the region of $6.5 billion, with employment in the region of 100000 to 120000. In fact, expenditure per GT increases as size decreases, so these figures are conservative. In addition, no provision is made for employment in naval shipyards.

3.3.6.1 Very large (post-Panamax) drydocks

At the beginning of 2003, there were about 265 drydocks in the world with a length of at least 215 meters and a clear breadth of at least 40 meters. Of these, about 100 are used primarily for shipbuilding and about 165 are used primarily for repair, although there is some overlap between the two groups. The geographic distribution of the 165 repair drydocks is shown in Table 3.xXX.

Most of the ships that require a very large drydock are tankers, the major trade routes for which are from the Persian Gulfto Japan, the U.S., and Europe. Repair activity in this size group should logically be concentrated in these regions. In practice, however, repair yards in Japan, the U.S., and Europe are unable to compete with those in Singapore and the Middle East.

Very large dry docks located in other regions are rarely utilized to their full potential. Very large tankers trading to the U.S., for example, lighter from offshore and are too big to get into the ports where the very large drydocks are located: as a result, the primary users of very large dry docks in the U.S. are cruise ships and offshore drill rigs. Many very large drydocks in North America and in Europe are idle, some because their age and cranage are unsuited to the needs of the modem ship repair industry. Some very large drydocks in South Korea were built for repair work, but have been converted to ship construction, while some in Japan were originally intended for ship construction.

Most of the drydocks in this category are graving docks, which are generally more economical in terms of construction cost than floating docks in this size range. All the remainder are floating docks.

TABLE 3.XXX Very Large (Post-Panamax) Drydocks

Region	*Countries*	*Docks*
North America	2	27
Central/South America	2	2
Northern Europe	11	42
Mediterranean	11	25
Africa	3	3
Middle East	3	9
South Asia	2	2
Southeast Asia	3	17
Far East	5	37
Oceania	1	1
World Total	**43**	**165**

TABLE 3.XXXI Large (Panamax) Drydocks

Region	*Countries*	*Docks*
North America	2	21
Central/South America	7	11
Northern Europe	12	50
Mediterranean	9	20
Africa	2	2
Middle East	2	3
South Asia	1	4
Southeast Asia	2	4
Far East	3	13
Oceania	1	2
World Total	**41**	**130**

3.3.6.2 Large (Panamax) drydocks

At the beginning of 2003, there were about 175 drydocks in the world with a length of at least 185 meters and a clear breadth of at least 32 meters but less than 40 meters. Of these, about 45 were used primarily for shipbuilding and about 130 were used primarily for repair. The geographic distribution of the 130 repair drydocks is shown in Table 3.xXXI.

Ships that require a Panamax drydock are of all cargo types, the trade routes for which are worldwide. Repair activity in this size group should logically be broadly distributed. In practice, however, repair activity is relatively low in developing nations and concentrated in the major ports of the major trading nations. Despite this, many drydocks in regions with relatively high costs, such as the U.S. and Northem Europe, are under-utilized. In addition, it should be noted that most of the shipyards that operate very large drydocks also operate at least one Panamax dry-dock and often one or more smaller dry docks of various sizes, in order to be able to serve multiple markets as efficiently as possible.

Most of the drydocks in this category are floating docks, which are generally more economical, in terms of construction cost, than graving docks in this size range. All but one of the remainder are graving docks.

3.3.6.3 Small drydocks

At the beginning of 2003, there were about 810 drydocks in the world with a clear breadth of at least 20 meters, but less than 32 meters. Of these, about 235 were used primarily for shipbuilding and about 575 were used primarily for repair. The geographic distribution of these 575 repair drydocks is shown in Table 3.xXXII.

Ships that require a small dry-dock operate worldwide and are of all types. Repair activity in this size group should logically be broadly distributed and it is: most of the business in this size range is contracted regionally. As in the preceding category, it should be noted that many of the shipyards that operate large drydocks also operate one or more smaller drydocks.

The great majority of the drydocks in this category are floating docks, which are clearly more economical than other types in this size range.The remainder includes a few small graving docks as well as several ship lifts and marine railways.

TABLE 3.XXXII Small Drydocks

Region	*Countries*	*Docks*
North America	2	89
Central/South America	15	44
Northern Europe	18	198
Mediterranean	16	81
Africa	13	17
Middle East	5	7
South Asia	4	18
Southeast Asia	7	45
Far East	5	67
Oceania	3	9
World Total	**88**	**575**

TABLE 3.XXXIII Very Small Drydocks

Region	*Countries*	*Docks*
North America	4	110
Central/South America	17	145
Northern Europe	17	600
Mediterranean	17	105
Africa	24	80
Middle East	10	30
South Asia	4	45
Southeast Asia	9	185
Far East	5	145
Oceania	5	55
World Total	**112**	**1500**

3.3.6.4 Very small drydocks

At the beginning of2003, there were at least 1500 drydocks in the world with a clear breadth of less than 20 meters. This figure is misleading, however, in three different ways:

1. the drydocks listed in the principal sources are clearly under-counted in the U.S., the former Soviet Union, and China,
2. many of these small drydocks can be used for either repair or construction, or a combination of both, and it is often hard to tell which, and
3. many of these small drydocks are transfer mechanisms and serve multiple repair positions, thus being effectively equivalent to multiple conventional drydocks.

The geographic distribution of these 1500 drydocks is shown in Table 3.XXXIII.

Ships that require a very small drydock operate worldwide and are of all types, including barges and other inshore craft. Repair activity in this size group should logically be broadly distributed and it is: almost all the ship repair business in this size range is contracted locally.

The drydocks in this category are of all types; floating docks, marine railways, ship lifts and a few small graving docks.

3.3.6.5 Other ship repair facilities

In addition to those *full-service* ship repair yards, which operate, some kind of dry dock, there are three other groups of repairers, none of which can be easily counted:

1. there are thousands of boat yards that handle small vessels with a crane or other mechanical device;
2. there are hundreds of *topside* repairers that work on ships at a cargo pier or mooring, possess no drydocks or even any permanent facilities at all, and concentrate on meeting a ship operators' need to minimize time out of service;
3. there are hundreds of manufacturers that provide maintenance services of various types directly to ship operators.

3.4 SUMMARY

The world fleet of ships, boats, barges and other craft owned by commercial and governmental organizations numbers at least 350 000, of which over 100 000 are ocean-going. These vessels are of at least 35 different types and countless subtypes. They range in size from tugs and patrol craft to ultra-large crude carriers and cruise ships, and in complexity from an inland hopper barge to a deep-water drilling rig.

The marine industry involved with this fleet is structured in five major sectors; ship design, shipbuilding, marine manufacturing, ship operation and ship repairing. Each of these sectors is managed by people with a marine education, whether in naval architecture or some related discipline.

It is very difficult to assess the number of different companies and governmental organizations in these five industries, but it must be at least 5000, even excluding all the thousands of single-vessel shipowning entities. In addition, these five major industries are supported by numerous smaller industries, not addressed here, that are primarily subsets of other industries, such as maritime and admiralty law, marine insurance brokers, ship brokers, shipping agents, ship breakers, and many others.

It is also very difficult to count the number of people who are employed in the marine industry. Including all the public-sector and private-sector personnel involved in all aspects of the industry, it appears to be at least 5 million.

The marine industry is often thought of as declining. This is a mistake that the industry itself needs to correct. Not only is the marine industry a growth industry, it can do nothing but grow for the foreseeable future. Three basic facts underlie this statement:

1. the demand for shipping is driven by trade, which is driven by consumption, which is driven by population. As a result, the demand for shipping grows at an annual rate of about 3%, measured in tonnage, and 2%, measured in numbers of vessels,
2. the average age of the world fleet is 18 years. This figure has not changed much in recent years, although it ought to decline because the number of vessels in the fleet grows. On average, therefore, at least 3% of the fleet needs to be replaced every year, and
3. The combination of 2% for growth and 3% for replacement means that at least 17 500 new vessels are needed every year, of which about 5000 are ocean-going.

In the absence of any economic alternative to the ship, therefore, the marine industry will continue to grow and it is this indisputable requirement that drives the industry's continuing worldwide effort to develop more efficient ship designs, more efficient construction methods and more efficient operating technology. And it is this force for change that drives those who make their living in the marine industry.

For an industry scorned by Wall Street as low-tech, its record of development is impressive. Fifty years ago, the containership, the bulk carrier, the gas carrier, the roll-on/roll-off ship, the reefer'ship, the cruise ship, the offshore drilling rig and the fast ferry did not exist. It is impossible to imagine what life would be like today if the marine industry had not achieved these technological advances.

There has been remarkable change in capacity as well as in the development of new ship types. Fifty years ago, the largest general cargo ship was about 13 500 tonne DWT, compared to containerships of 105 000 tonne DWT today; the largest tanker was 38 000 DWT, compared to 550 000 tonne DWT today; and the largest passenger ship was 85 000 GT, compared to 140000 GT today.

It is interesting to speculate where the marine industry's skills will take it in the next fifty years, especially considering the acceleration in the rate at which technology can be developed. In 2050, will there be an economic alternative to the ship for ocean transportation? What new ship designs will be developed? How big will ships be and how fast will they go? Will the break-bulk cargo ship have disappeared completely? Will the fuel still be oil? If so, what will drilling rigs look like? How will the fishing fleet (the one sector that has not changed much in the past 50 years) have developed?

When we take the long view and consider the marine industry as a whole, we see an industry with a remarkable record of achievement. Unfortunately, there is also a negative side. The demand for shipping does not grow at a uniform rate in every sector: it can be wildly cyclical. Although this affects the stability of the shipping industry, it has a greater impact on the shipbuilding industry. The high levels of capital investment required for efficient shipbuilding and the relatively long time required to build individual ships make it very difficult for shipbuilders to operate efficiently in an unpredictable environment. As a result, the shipbuilding industry has an unfortunate record both of economic failure and of dependence on government support. The shipping industry, for its part, has serious problems of crew training, safety, environmental consciousness and public relations that need to be addressed as soon as possible.

The great challenge for the marine industry in the 21st century is not, therefore, technological; the technological challenges can and will be met. The challenge is economic: Can the marine industry meet the growing and changing needs of its various markets and simultaneously achieve a reasonable level of internal stability and security?

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Chapter 4

The Ship Acquisition Process

Charles R. Cushing

4.1 INTRODUCTION

The acquisition of a new ship, from the buyer's or shipowner's perspective, is a major capital expenditure undertaking. It should follow a four-phase process, namely:

1. planning,
2. design,
3. commercial activities, and
4. production activities.

There are a number of different paths to obtaining new, expanded, enhanced or replacement marine transport capacity. These include:

- new ship construction,
- secondhand purchase,
- lease or chartering (bareboat, time or voyage),
- ship conversion (jumboizing, re-engining, etc.),
- contract of afreightment, and
- ship-sharing or pooling tonnage.

This section will focus on new ship acquisition or ship design and construction. However, many of the methods suggested here also apply to ship conversion projects.

The four-step method described here is a procedure that has worked well in countless projects. However, the reader should be aware that there are other procedures, which might, under appropriate circumstances, be preferable. One such approach is to eliminate the design phase and some of the commercial activities and, instead, purchase a standard vessel from a shipyard. The disadvantage of this method is that the vessel may not exactly meet the shipowner's needs, such as speed, capacity, etc., and the limitations in the selection of machinery and outfitting. The method truncates the competitive bidding process and possible loss of competitive technological advantage over competitors. Advantages may include a lower price due to series-built, multiple-ship economics at the yard, proven design and possible faster delivery. Also, government procurement methods (particularly naval vessels) may involve different procedures. Design-Build is a currently in-vogue approach. However, for new merchant ships, the process provided herein is a proven, traditional, conventional and effective approach.

4.2 PLANNING

4.2.1 Introduction

Planning has always been an important part of any major project activity. However, it was not raised to a management science until the twentieth century. U.S. industry started using rudimentary management strategy procedures in the 1920s and 1930s. During World War **II,** the U.S. Government developed the process into what was first called *strategic planning.* It became a management science in the U.S. during the 1960s and spread worldwide during the 1970s and 80s. It further evolved during the 1990s to become a part of strategic management. However, the fundamentals of strategic planning have remained the same.

This first phase involves strategic planning which has been defined as *The continuous process of making present entrepreneurial (risk-taking) decisions systematically and* *with the greatest knowledge of their futurity; organizing systematically the efforts needed to carry out these decisions; and measure the results of these decisions against the expectations through organized, systematic feedback* (I).

Elements of strategic planning can and should be applied to the new ship acquisition process. However, the principles are the same for other types of major capital projects; the construction of a port, oil refinery, bridge, building, factory, etc.

The strategic planning process begins with an assessment of the environment associated with the enterprise being considered. This environment includes both the internal environment within the organization undertaking the activity, and the external environment in which the ship will function.

4.2.2 Environmental Analyses

The internal environment will consider the organization's strengths and weaknesses, such as:

Technical Resources
- a. engineering,
- b. research,
- c. patents,
- d. innovative attitude, and
- e. willingness to undertake technical risk.

Financial Resources
- a. assets,
- b. cash position,
- c. debt-long and short term,
- d. profitability, and
- e. financial stability.

Human Resources
- a. number and types of personnel,
- b. project management skills, and
- c. capability to staff the new project.

Management Resources
- a. project control,
- b. communications, and
- c. organizational structure.

The external environmental analysis looks at threats and opportunities and depends upon the nature of the trade. It essentially looks at the trade and competition. It will include:

Market Size
- a. volume tonnage, cubic, number of passengers, etc.,
- b. market growth and trend, and
- c. potential for new markets.

Market Description
- a. commodities, and
- b. fluctuations in flow; that is, seasonably.

Trading Pattern
- a. pendulum (that is, back and forth),
- b. round-the-world,
- c. multi-leg (that is, triangular, etc.),
- d. direct,
- e. land bridge,
- f. tramp, and
- g. other.

Competitors
- a. number,
- b. market share,
- c. strengths and resources,
- d. potential alliances, and
- e. service factors (that is, delivery times, reliability of schedule, etc.).

Economics
- a. freight rates,
- b. rate trends,
- c. conferences and their rules, and
- d. potential for rate wars.

Physical Environment
- a. distance,
- b. sea and weather conditions,
- c. channel and harbor depths,
- d. canal and air draft restrictions,
- e. tides and currents, and
- f. vessel traffic controls.

Port Conditions
- a. berth availability and priorities,
- b. cargo handling productivity,
- c. longshore labor availability, productivity and stability, and
- d. cargo availability.

Barriers to Entry
- a. conference system,
- b. government restrictions, tariffs, grants, cargo reservation, etc.,
- c. rate cutting,
- d. excess shipping capacity, and
- e. shipper loyalty.

4.2.3 Strategy Development

After a thorough analysis of the external and internal environments, planning enters the second phase, namely Strategy Development. The corporate objective must be identified. While it is often assumed that profitability is the sole objective of a firm, in reality corporate objectives have to be set in a number of other areas (see Chapter 6 - Engineering Economics). These can include:

- profitability,
- return on investment,
- market share,
- growth,
- stability,
- product or service quality,
- customer satisfaction,
- meeting the market needs, and
- competition.

Drucker (2) feels that objectives have to be set in eight key areas in a business:

1. marketing,
2. innovation,
3. physical resources,
4. financial resources,
5. productivity,
6. human organization,
7. social responsibility, and
8. profit requirements.

It is often difficult to get management's consensus on the objectives of the firm. Since *objectives are the fundamental strategy of a business,* every effort must be made to get agreement on the objectives.

A statement ofthe company's mission is required, concerning the markets to be served, the services to be provided, and how the company's resources will be used to provide those services.

Strategic objectives should consider the future and how the company's resources will permit it to succeed in that environment. The strategic objectives provide measures of the success in meeting the mission of the company.

Strategy development is the phase in which the courses of a«tion are developed, which will meet the strategic objectives previously identified. MarAd recommends developing a number of strategic options, which can be tested and compared. This usually requires the preparation of pro forma financial projection for each alternative. Each alternative is then analyzed against the corporate objectives. The alternative then may be optimized to achieve the best possible value.

With regard to technology, it should be kept in mind that up to this stage the decision has not yet been made as to whether the vessel to be acquired would be a new vessel, a second-hand vessel, a conversion of an existing vessel in the fleet, the chartering in of existing tonnage, or whether a vessel is even required. The development of each option should be complete enough to include market share estimate, required corporate resources and financial pro forma. If computers are used, it is possible to carry out simulations and sensitivity analyses more easily (3). In addition to testing the options against quantitative financial requirements, other criteria should be considered such as minimization of risk, optimal use of corporate resources, and the impact of unexpected changes in forecasts.

The threats to any strategy that is developed should be identified. Napuk (4) urges this step to be an integral part of the planning process for two reasons. First, if the risks are too great, the project can be aborted or modified to reduce the risk. Second, if the project doesn't materialize according to plan, an alternative plan will be in place.

A fundamental part of the implementation of the stfategic plan is the development of a plan for its commencement. This entry plan addresses such issues as the timing and selection of a starting date. It calls for scheduling and a timetable. Definitive coordination between all segments of the corporation and external organizations, which are effected by the plan, is essential. The marshaling of resources such as personnel, capital, equipment, etc., is part of the entry plan. Governmental actions, permits, licenses, etc., and political support, where necessary, must also be anticipated. Such an entry plan is useful in coordinating the various business plans discussed below.

No less important is the development of exit plans. This should not be regarded as defeatism. Rather, it is prudent to consider as many options as possible in the event that the strategic plan does not develop as anticipated. A variety of alternatives are possible depending upon the nature of the unforeseen events. These could include committing additional resources, shifting priorities, even reducing effort or withdrawing completely. These exit options may also consider totally scrapping the plan or selling, swapping, merging or gradually withdrawing. The benefits and drawbacks in these plans are available to be considered while the strategic plan is in force.

4.2.4 Implementation

The first two planning phases are transformed into practical and concrete business plans, capable of being executed. Strategic planning should not be mistaken for business planning. Strategic planning involves the entire organization whereas business planning may only involve one specific aspect of the strategic plan. A business plan usually involves a program for the implementation of one of the objectives resulting from the strategic plan.

The various implementation plans for the marine industry and transportation services may be treated in the same manner as in more traditional strategic plans, such as manufacturing. These may include:

Marketing plan: the identification of specific market segments, customers, their needs, and sales methods to be used.

Competitor plan: the actions to be taken to overtake, bypass, forestall, overwhelm, join or otherwise counter the position of competitors.

Operations plan: the detailed operational plan for carrying out the strategy, including the sequence and phasing of such actions.

Financial plan: the budget and controls to be used for the business plan, including cash flow projections and capital requirements.

Technology plan: the plan for the development or acquisition of new and competitive techniques and equipment; that is, ships, handling systems, etc.

Organization plan: the detailed organization structure and the use of the company's human resources to carry out the strategic plan.

Corporate development plan: the plan for integrating and coordinating the strategic plan into other plans within a large organization's other plans to best meet the corporation's overall goals.

The final step in strategic planning is the implementation of the plan. The effective communication of the details of the plan to all participants is an essential step. The progress of each of the business plans in meeting goals and criteria must be monitored and corrective action applied, not only to plans which are failing to meet goals, but also adjustments to meet differences from forecasts.

The complexity of researching, designing and building a vessel is apparent. The criteria to be used for the design and acquisition may involve hundreds of factors. For the sake of good order, and in order to communicate a common standard to the entire team, it is essential that these criteria be set down in a mission statement.

4.2.5 Mission Statement

The principal results of the Technology Plan should form a part of the mission statement. The objectives of the firm or shipowner and key elements of the company's strategic plan should also be embodied in the mission statement.

A second purpose of the mission statement is to prevent the unintentional or accidental deviation from the original objectives. When and if these early objectives change, the mission statement records these modifications. The mission statement becomes a control document that aids management and the vessel acquisition team.

Therefore, the mission statement becomes a centralized compendium of information necessary to design the vessel and criteria to test its economic feasibility.

4.2.6 Economics

Throughout the entire ship acquisition process, the use of engineering economics is essential. During the strategic planning stage, economics are used to develop and evaluate strategic alternatives. Engineering economics are also used in developing the technology, financing and business plans. The mission statement should also address the objectives of the firm, including the financial objectives and criteria.

During the designing phases and especially in the conceptual and preliminary design, engineering economics are used both to optimize and select alternatives. As the acquisition process proceeds, the project manager should continuously update the economic model developed at the outset.

During the commercial stage of the ship acquisition process, economics are important in evaluating various financing alternatives and shipbuilding proposals. The final contractual terms also give the project manager an opportunity to update the initial projections.

While shipbuilding economics are less important to the shipbuilder during the production phase, it is still essential that good economic procedures and methodology be followed when the shipyard proposes design alterations. Also, during the production phase, there are many opportunities for the budget to go awry. There is constant pressure by the shipyard to charge extra costs. Operating personnel in the shipowner's company tend to make changes and to use the latest models of equipment, which are put on the market after the shipbuilding contract has been signed. The project manager must be diligent, if not somewhat hard-nosed about maintaining budget and schedule. Chapter 6 - Engineering Economics, covers many of the principles that are important in the ship acquisition process.

At the end of this phase the shipowner will have a complete Requirements Definition as described in Chapter 7 - Requirements Definition.

4.3 DESIGN

4.3.1 The Design Process

The second major phase in a ship acquisition program relates to design. Design, while having many meanings, in this context means to prepare calculations, technical model/documentation (drawings), specifications, and to support these with experimental testing as required. The design phase forms a transition from the requirements of the planning phase. It lends form and substance to the mission statement by establishing a configuration, shape, dimensions, layout and other characteristics, which can be represented visually, which can be presented on paper or in a computer as a 3D product model. Chapter 13 - Computer Based Tools address this topic. It is the point at which the center of effort shifts from management science to design, particularly, naval architecture and marine engineering.

This design and engineering phase of the ship acquisition process progresses through distinct and increasingly more definitive stages (5). These are:

- concept design,
- preliminary design,
- contract design, and
- detailed design or production engineering.

It should be noted that the fourth design stage, the Detailed Design, wherein the working drawings are prepared, is usually executed after the shipbuilding contract is signed. The shipbuilder usually prepares the working and shop drawings. There are rare occasions when a shipowner may cause the detailed design to be carried out prior to contracting with a shipyard. This is more likely to be done for smaller vessels such as tugs, service craft or specialized vessels or where the shipowner may purchase a set of working drawings from a designer or from a shipyard. The shipowner may buy the working drawings for an existing ship. He may do this because the shipyard he is contracting with may lack the necessary skills, it may shorten delivery time or he may want to duplicate ships already in his fleet.

However, the more customary procedure is for the shipyard to prepare the detailed drawings during the production phase, and hence this fourth engineering stage will be discussed in Section 4.5 - Production.

There is no question that ship design is engineering work and as such should be carried out by professional engineers trained in naval architecture and marine engineering. Engineering may be defined as the application of science and mathematics by which the properties of materials and energy are made useful to people through the creation of structures, machines and systems.

The process of designing involves conceiving, planning, and calculating, and then sketching, drawing and/or modeling the concepts to give them graphic form. Yoshikawa (6) explains design in another way, as a mapping from *afunction or specification space* to an *attribution space.* The design effort is supported by carrying out whatever calculations, model testing, research, development and experimentation are necessary to assure that the engineering effort is sound.

The design effort may also include the preparation of written materials, which aid in conveying the ideas of the designer and in explaining the working of the device or system. These written explanations may take the form of simple or extensive notes on the drawing, or in the form of written specifications in booklet or book form.

There is a popular misconception in the marine field that specification preparation is an independent, non-engineering activity and can be prepared by semi-technical or non-technical personnel. Often, technical writers, with little marine experience, or no formal engineering education will undertake the preparation of a shipbuilding specification.

The modification or reuse of specifications originally prepared for other designs is a bold and imprudent approach, sometimes with disastrous results. This sometimes also occurs when managers attempt to save legal fees and avoid consultation with lawyers by reusing previous contracts as a model and write their own shipbuilding contracts.

The written portion of a design may also take the form of reference to industry standards, classification rules, governmental regulations, manufacturers' specifications, or shipbuilders' detailed standards. These then also become an integral part of the design. It is very important that the designer incorporating these materials be thoroughly familiar with such documents in order to avoid ambiguities arising from the existence of alternative approaches or features which may appear in those documents but may not be intended by the designer to find their way into his design. It is also essential that reference be made to the most current issue of those documents as they are usually under constant review and revision.

It must be borne in mind that drawings and written specifications are both integral and intertwined parts of the design. They are meant to explain each other. They both represent engineering effort and as such need to be prepared by and thoroughly checked by engineers (see Chapter 9- Contracts and Specifications).

The design effort might also involve modifying, extending, or otherwise building on previous designs, or synthesizing other designs. Hence, another necessary design activity involves research into both previous specialized work in the field, and current or state-of-the-art developments in the field. While it is reasonable to assume that the designer is well informed in these matters, it must be recognized that the accelerating pace of technology, worldwide, and the proliferation of research and technical information makes it essential that the designer be current and up-to-date. The prudent designer will also be aware of the requirement that the design-build-implementation process is a lengthy process, and the ship being designed is expected to operate and compete effectively for as many as 20 to 30 years after delivery (for naval ships often up to 50 years). Hence, just being up-to-date is not sufficient. The designer should also be aware of the status of research and development, worldwide, and be alert to potential breakthroughs in the many disciplines in the marine field.

The designer must also factor into the design the manufacturing or shipbuilding processes and procedures so as to create *production-friendly* features in order to assure that the vessel construction costs will be minimized. This requires a strong appreciation, by the designer, of the most current and advanced procedures used by shipyards. The same applies to machinery and material selection (see Chapter 14 - Design/Production Integration).

Research and development are also part of ship design process. Pugh (7) states that *"research and development are mutually exclusive but interactive activities, each having completely different characteristics"* and that *"research is a necessary and vital part of ship design, so is development."* In the research phase, engineers seek new principles and processes using scientific concepts, experimental methods and inductive reasoning.

The art of applying knowledge and scientific principles to useful purposes is the essence of design. Design requires *the imagination to conceive original solutions to problems, and the ability to predict performance and costs.* The fundamental task of design is problem solving, a process which involves analysis of the stated problem, establishment of methods of solution, restatement of the problem in elemental questions or terms, and answering these questions or solving these problems by deductive reasoning from existing systematized information, knowledge or principles, or in the case or original or new systems, by creative synthesis. Synthesis prevails at the conceptual design stage whereas analysis is more prevalent in the detailed design stages. Buxton (8) tells us *"design is the essence of engineering."*

Design is the step in engineering where shape and form evolve, where structure is defined, where materials are selected and components to be assembled are identified.

The engineer is usually faced with solving problems with conflicting requirements. These may be physical (minimum weight), economic (minimum cost), social (maximum safety) environmental (minimum impact), etc. The engineer must resolve these conflicts and search for *optimum* solutions. The optimizing is done with regard to the objectives of the firm, which were identified in the planning phase (see Chapter 5 - The Ship Design Process, Chapter 11 - Parametric Design, Chapter 13 - Computer Based Tools).

Since 1957, it has been customary to describe the ship design process as a design spiral. J. Harvey Evans, a professor at MIT, used the spiral to explain the design process as an iterative or repetitive stepwise method, moving from a general set of requirements to converge on a detailed and definitive final design. Numerous other authors, including Buxton, Rawson, Atkinson, Eames, and Drummond, Gilmer, D' Archangelo, have also used'the design spiral to illustrate the process. In all cases, the spokes of the spiral represent parameters or steps in the process, arranged in what the designer considers a logical sequence. The design proceeds by progressively improving each parameter, while holding all other features constant.

U.S. Naval designers depict the same design activity model in a graphical sequence of block diagrams, which they call *Current Design Sequence.* These stages, briefly, include:

- definition of requirements,
- mission analysis,
- concept formulation,
- preliminary design
- contract design, and
- detailed design.

Other designers use bounding, step-back and set-based design which are all based on finding the most effective way to design (see Chapter 1 – Introduction, and Chapter 5 - The Ship Design Process).

Prior to 1970, an immense amount of labor was required in order to achieve even one circuit of the design spiral. Work done at the conceptual stage was often crude and approximate. It was based on common relationships and ratios, and was only a first approximation. The search methods or number of circuits of the spiral at the latter stages were also constrained by available resources.

The availability of high speed computers, and design software *packages* or modules such as for structural design, sea loads, speed and power prediction, HVAC, pipe flow, heat balances, etc., have raised the possibility that more efficient optimization methods may be applicable. However, the availability of such computers and software has not precluded the necessity of following the fundamental ship deSIgn sequence.

Each stage serves a purpose, has its unique characteristics, and is essential in an orderly ship acquisition program. The process of ship design and the purpose of each stage are discussed fully in Chapter 5 - The Ship Design Process. It will be briefly covered here to give a complete understanding of the ship acquisition process.

4.3.2 Concept Design

The step in the design process that follows data gathering and development of the mission statement is the *Concept Design* stage. It is the point where the project starts to develop form and dimension. The Concept Design stage involves the transformation of a qualitative set of requirements into an early design configuration, with some of the principal characteristics defined. The Concept Design effort usually results in a sketch or drawing, partially or fully dimensioned, and may also include developing a written description of the concept. It will normally include one or more design alternatives.

The Concept Design stage has unique and distinctive characteristics, which differentiate it from other phases of ship design. Assuming that new ships are being considered, the concept phase is one where synthesis, the combining of conceptions into a coherent whole, takes place. Before analysis and optimization can take place, it is necessary to have models to analyze.

The Concept Design stage requires a small number of engineers and these people should be highly creative and innovative. Gilmer estimates that the Concept Design stage often takes between 4 and 80 man-days. While it is very difficult to put such bounds on the amount of time required for conceptual design, it is agreed that conceptual design requires one to several orders of magnitude less effort than preliminary or contract design.

4.3.3 Preliminary Design

The second design stage in the evolution of a ship is the *Preliminary Design.* The preliminary design is an engineering effort, which builds on, and provides much greater detail than does the concept design. It is a second iteration in the design process. For those who think of ship design in terms of the design spiral, it is the second circuit of the spiral, which is meant to converge on a more accurate and improved set of vessel characteristics.

The preliminary design is also meant to provide a greater level of detail, especially identifying and defining those features, which have a significant effect on other characteristics of the ship, including cost. For example, a calculation of the longitudinal strength of the hull and the development of the midship section permit a more accurate calculation of the weight and center of gravity of the vessel. This, in turn, permits a more accurate calculation of draft, deadweight capability and stability, etc.

The preliminary design should provide sufficient detail to permit the verification of both the technical and economic feasibility of the ship.

This level of detail is sufficient to permit a new building or construction cost estimate to be made. This usually requires just the principal dimensions, weight estimate and type of main engines. Any special features of the vessel, which significantly affect the construction also, need to be identified. These could include such features as cargo handling equipment, tank cladding, stabilization systems, etc.

The preliminary design also provides sufficient detail to permit a reasonably accurate operating cost estimate to be made. The operating cost estimate relies on such inforination as number of crew, fuel and lubricating oil consumption and an estimate of maintenance costs based on the outfitting and coating systems used.

The preliminary design also provides sufficient information to permit estimates of the revenue generating capability of the vessel to be made. These calculations rely on deadweight or other cargo capacity estimates and trim and stability calculations.

The preliminary design also permits an assessment of the technical feasibility of the ship. The compatibility and stowage of cargoes can be verified. The ability of the vessel to operate at various conditions ofloading, including the ballast condition, can also be reviewed. The defined level of automation can be correlated with the assumed or planned crew size and designations.

Prior to the advent and widespread use of computer in preliminary ship design, each iteration or circuit around the design spiral was costly and time consuming. Design shortcuts, approximations and rules-of-thumb were standard practice. While the accuracy improved with successive iterations, there was less likelihood of achieving precisely optimum designs. Also, the limitations in scheduling, manpower and financial resources for design often truncated optimizing efforts or restricted the exploration of design alternatives. The extensive use of computers now permits greater accuracy and more alternatives to be examined, all with less effort and in a dramatically shorter time. For this reason the traditional design spiral approach as a search technique for converging on a feasible and optimal design may be replaced by other optimizing techniques. For example, a matrix or grid approach is possible, wherein a large array of design alternatives can be quickly explored.

4.3.4 Contract Design

The third design stage involves the preparation of both the contract specification and the contract drawings. The primary purpose for preparing contract specifications and drawings is to create a set of documents which accurately describe the vessel to be built, and can be used as a basis for agreement between the buyer (or shipowner) and builder (shipyard). The level of specificity at this stage is not fixed by industry practice. Rather, it depends on a number of factors, including the size and complexity of the vessel, the presence of novel features, the contractual risks in dealing with certain shipyards, etc.

The level of detail in the specification and drawings should be just sufficient for both parties to fully understand the requirements of the other; that is, a meeting of the minds.

The specifications are meant to be a companion document to the contract plans and the contract itself. In the event that there are contradictions between the contract, specifications and drawings, the generally accepted hierarchy is that the contract terms prevail, followed by the specifications and lastly the drawings. This is usually explicitly stated in the contract and specification.

There is no generally agreed upon format for specifications. The U.S. Maritime Administration's standard specification has been found to be thorough and logically arranged. When given the opportunity, Japanese and Korean shipyards prepare their specifications, divided into three volumes, namely hull, machinery and electrical. The Norwegian Ship Research Institute (Norges Skipsforskningsinstitutt) has organized their standard specifications so as to simplify design, purchasing and manufacturing. Each section ofthe specification is coded to a standard. The U.S. Navy breaks down the components in their vessels into their Ship Work Breakdown Structure System (SWBS). This classification system, a military standard, MIL-STD-881A, is used to integrate design, engineering, production, and logistics. This is a three-digit preliminary and detail design system. An expanded five-digit SWBS system enhances the purchasing, maintenance, cost accounting, storing, and overhaul procedures.

The specification and drawings should be prepared to thoroughly describe the vessel and those features which the shipowner truly needs or desires. However, the shipowner should realize the excessive specificity could inhibit the ingenuity of a builder, and in the end, produce a more costly vessel, for which the shipowner will pay extra. At times it is desirable for the shipowner to specify machinery or equipment by brand name. This is a normal and sometimes necessary practice. However, where it is not necessary, it should not be done because it constrains the shipyard in its price negotiations with suppliers. If the suppliers know that they are written into the specifications, they will be reluctant to provide their lowest prices to the shipyard.

Engineers should prepare the specifications, since many of the features described in the specifications involve or impact upon engineering decisions. There is prevalence on the part of many shipowners to have non-technical operating staff prepare the specifications. This is to be deplored as it can lead to serious mistakes or weaknesses in the design.

A second reason for carrying out the contract design is to increase the amount of detail and improve the accuracy of the design. This, in turn, permits the designer to continue assessing the economic and technical feasibility of the design, but with increasing accuracy, greater reliability and less risk.

During both the preliminary and contract design efforts, a great many calculations are performed. These do not usually form a part of the contract package. However, if provided to the shipbuilder, they should be treated formally, carefully checked and documented and kept with the design package. While many shipyards or preparers of the working design drawings prefer to re-do these calculations, some do not, and therefore in their case, the calculations are useful in simplifying or verifying ongoing design work. As most contracts place full responsibility for performance of the ship on the shipbuilder, it is essential that they re-do the calculations for their own protection. If they do not and the performance is not met it often becomes the basis for claims.

The use of guidance drawings is a practice often encountered. The purpose is to convey to the shipyard some of the engineering effort that has been carried out, leading to the contract design. However, since the guidance drawings do not carry contractual obligations, they often lead to misunderstandings between the buyer and the shipyard. Both parties need to be very clear regarding what their obligations are with respect to guidance drawings. The use of guidance drawings should be avoided, wherever possible.

4.3.5 The Role of Vendors

Machinery, equipment and outfitting costs can represent between 50 and 70% of the cost of a ship and as high as 75% in the case of naval and passenger ships. The importance of manufacturers and suppliers in the ship acquisition process cannot be over emphasized. The shipowner and/or his naval architect should work with the vendors early in the design stages. The vendors are in a position to provide up-to-date, valuable product information to the ship designers in at least the following areas:

- physical dimensions,
- weight,
- capacity or capability,
- preliminary cost or list prices,
- power and auxiliary service (air, cooling, water, etc.) requirements,
- maintenance, service and spare parts requirements,
- installation drawings, and
- noise data.

The last item is important today because of the growing awareness of industrial health environmental concerns.

Vendors are also very helpful, if not somewhat biased, in defining the technical capabilities of their products, and contrasting them with those of their competitors. Keeping this bias in mind, the designer is in a much better position to evaluate the relative merits of alternative types of equipment, and like items from different vendors.

A shipowner may already have a relationship with certain engine manufacturers and other suppliers, and therefore, have preferences, which should be recognized when preparing the design and specifications.

It is sometimes useful for the shipowner to engage in negotiations with key suppliers, at an early date, even though all parties know that the yard will purchase the materials. Of course, in some cases it is possible for the shipowner to purchase some of the materials and furnish them to the yard as shipowner-supplied-items. However, in doing so, the shipowner takes on liabilities regarding delivery and unit performance. When things go wrong, there are often large claims by the builder.

Some of the areas beneficial to the shipowner, which can be negotiated beforehand, include dealing with the vendors in:

- providing crew training at low or no cost,
- assisting in the installation drawing plan approval,
- providing factory representative or installation engineer through start-up and testing,
- providing annual turnkey maintenance contracts at competitive rates,
- establishing service centers and fully stocked spare parts warehouses convenient to the shipowner's areas of operation, and
- favorable warranty terms.

The shipowner must be aware that the efficiency of the shipbuilding process is tied to good shipbuilder supply chain management. If the shipowner is overly specific, it may result in a higher contract price because of possible disruptions to shipbuilder-supplier long-term agreements, inventory, scheduling considerations, etc. The shipowner should be prepared to be flexible, where possible. One mechanism frequently employed at the pre-contract stage is the agreement on a vendors list, with up to three vendors or models, in each category, from which the shipbuilder is free to choose when he is ready to order. The vendors' are definitely part of the shipowner's vessel acquisition team.

4.3.6 The Role of the Regulatory Bodies and Classification Societies

The nature of regulatory bodies and classification societies should not be confused. The regulatory bodies derive their authority from statute. They publish and enforce regulations, such as in those found in the Code of Federal Regulations (CFR). Designers and shipowners should also be alert to the periodically issued USCG N.V.I.C.s and notices of proposed rule making. The USCG permits some of their regulations to be administered by the classification societies. Foreign governments will sometimes permit classification societies to act on their behalf. The U.S. Federal agencies, which shipowners and ship designers will have to deal with, can include:

- U.S. Coast Guard (USCG)
- Federal Communications Commission (FCC)
- U.S. Public Health Service (USPHS)
- U.S. Maritime Administration (MarAd)

Indirectly, the following may have an impact on U.S. commercial ship design and operation:

- Environmental Protection Agency (EPA)
- Occupational Safety and Health Administration (OSHA)
- U.S. Navy

U.S. ships may also have to comply with U.S. State and municipal regulations, particularly with regard to air pollution, collision avoidance, mooring and other areas. When operating abroad, U.S. ships may also have to comply ~ith local national and industrial rules and regulations such as Australian Harbor Workers Rules, Indian Factory Acts, etc. U.S. vessels will also face port state control to assure that they comply with international conventions.

It is in the shipowner's best interest to assure that his designs meet the latest regulations (and even anticipate impending regulations), before negotiating and contracting. To this end, at the very least, the designers should confer with the cognizant regulatory bodies and class during the design period. The regulatory bodies and classification societies can be very helpful in suggesting technical alternatives. As such, regulators and class should be regarded as part of the ship acquisition team, rather than as adversaries.

4.3.7 Model Testing

The confirmation of power predictions at the preliminary and contract design stages can be carried out with towed and self-propelled tests at independent experimental model basins. These are especially useful when new or novel hull forms are used or the vessel's speed and power levels are high. Doing this testing at an early stage precludes expensive and disruptive changes, for power deficiencies, after contract signing. Other testing, which can be carried out, depending on the intended operations of the vessel, and the size and complexity of the size, cost and number of ships, can include:

- power prediction in still water,
- power prediction in regular waves,
- power prediction in irregular waves,
- power prediction in oblique waves,
- optimum trim tests,
- steering and maneuvering,
- seakeeping and deck wetness,

- ship motions,
- wake field,
- separation of flow,
- streamlines, for bilge keels,
- tests in ice,
- mooring loads, and
- propeller load, vibration and cavitation.

Computational Fluid Dynamics (CFD) has proven useful as a substitute for some model tests. Wind tunnel tests are also useful, in some cases, for stack exhaust, ventilation, wind load and superstructure streamline considerations.

Some of these tests can be carried out after contract. In fact, having the shipyard participate in the final resistance and power tests, gives them more comfort with their contractual speed guarantees. The propeller tests may be carried out together with the propeller manufacturer selected by the shipyard. Responsibilities for the costs of the various tests and technical performance should be carefully defined in the specifications and/or contract.

4.4 COMMERCIAL ACTIVITIES

4.4.1 Introduction

The third phase in the ship acquisition process mainly involves commercial activity. It includes soliciting bids, negotiating, contracting and financing. This third phase requires the expertise of professionals in these areas. The extent to which the shipowner may need to reach outside for assistance depends on the skill levels and experience within the shipowner's organization. It is likely that, on a very large program, the shipowner would need, or at least benefit from, the talents of experts in these different disciplines. It is not usual for a shipowner or his staff to acquire a few vessels over a short span of years. However, an admiralty attorney, naval architect, or a purchase and sale broker probably will be involved in a greater number of new building transactions for many clients in the same period. Hence their breadth and depth of experience will greatly exceed those of a typical shipowner's staff. On the other hand, the shipowner's staff will be much more familiar with the shipowner's needs and methods. Hence, a team approach, using the talents of both insiders and outsiders, tends to be a more effective overall solution.

The Commercial Phase essentially consists of the following steps:

- selection of yards for invitation,
- request for expression of interest,
- invitation to bid,
- bid analysis,
- preparation of pro forma contract,
- negotiations,
- financing, and
- contracting.

Each step, except financing, should be carried out in sequence. The financing efforts may begin long before the Commercial Phase begins, even as early as the Planning Phase. As the project proceeds through the Commercial Phase, price, delivery, financing terms and other vital details become better known and more precise. Throughout the Commercial Phase, the project should be continuously measured against the original objectives and the mission statement. Any departure should be deliberate and for good cause. The project and any deviations should also be continuously measured against the agreed upon economic criteria.

This continuous review may indicate that changes should be undertaken in the design, business plans or other aspects of the project.

4.4.2 Selection of Yards for Invitation

There are over 500 shipyards in the world capable of building ships of at least 5000 DWT in size. Obviously, it is impractical to invite everyone of these to participate in a shipbuilding bidding program. It is therefore necessary to limit the number to be invited. The reasoning used in making such a selection may be based on a number of factors. These attributes of the yard include:

- facilities,
- technical capabilities,
- expenence,
- order book position,
- geographical location,
- financing capability,
- customer satisfaction, and
- labor or political unrest.

The number of yards to be invited will depend on the size or value of the order, with the larger number of ships or complexity, usually requiring more yards to be invited.

4.4.3 Request for Expression of Interest

This step calls for making a simple, brief inquiry from each of the selected shipyards. The inquiries, which have been sent by telex, but more recently by facsimile or e-mail, outline the shipowner's intended order (number, type, and size of vessels). It asks for the shipyards to respond and state whether they are interested in bidding on the project.

4.4.4 Invitation to Bid

The next step in the commercial process is to formally request proposals from eligible shipbuilders. The invitation to bid is sometimes called *a request for proposals* (RFP). The necessity for carrying out this step formally includes a consideration of the fact that the relationship between requester and bidder has legal liability implications. Also, unless the responders submit proposals in a consistent manner, such as on a standard form, the analysis of the bids becomes extremely complex. The formal request for proposals also helps the project managers to maintain a consistent and reliable schedule for the commercial phase of the acquisition process.

It is customary and prudent to give the bidders sufficient time to prepare a well thought out and studied proposal. Too short a bidding period will cause the bidders to have to take short cuts in their design calculations and to estimate, rather than calculate their costs with the necessity that some margins will be included, resulting in higher bids.

On occasion errors in the design or specifications are found during the bidding period. Also, the shipowner's requirements may change during the bidding period. These may require sending out an addendum or addenda to the specifications and/or revisions to the drawings. An extension in bid due date may be appropriate.

The shipowner may want to encourage bidders to use their ingenuity to propose alternative design features or other ways to enhance their proposals. However, for purposes of consistency and to simplify analyses, each bidder should be required to include, with such changes and innovations, a basic proposal strictly in accordance with the bidding documents.

4.4.5 Bid Analysis

Upon close of bidding, the shipowner should promptly analyze the proposals received. The analysis phase can be complex if the bidders have not followed the formal procedures laid out by the shipowner. The analysis can be further complicated if the bidders take exception to any portion of the design or contract; or provide alternatives; or propose complex financing schemes.

If there are a large number of responders, the initial *cut* can usually be accomplished by ranking the proposals by price. Those that are obviously too high are rejected. Nevertheless, every proposal should be carefully read before rejection. A pricey proposal may contain other features, which are important and desirable to the shipowner. Some bidders may intentionally provide a high price for the shipowner's design, but a much more competitive price for their proposed alternatives.

The next step depends very much on the type of bidding procedure conducted. In the event that procedure calls for sealed bids to be publicly opened and award is based solely on low price, which is often the case in the procurement of government vessels, the analysis is simple and the result is evident, almost by inspection. However, the commercial buyer more usually opens the bids in private and reserves the right to select or reject any or all bids, at his discretion. After shortening the bidding list and carrying out the matrix analysis, the shipowner next creates a short list.

Courtesy and fairness dictate that the other bidders be notified at the earliest possible date of their rejection, so that they don't reserve building capacity for orders that will never materialize.

It is not only courteous and fair, but also good business practice to thank each bidder, in writing, and to advise each bidder why his proposal was rejected. When treated fairly, yards will be more willing in the future to put effort into responding to other RFPs. The short listed bidders should also be notified, advising them that they are on the short list. Negotiations can then begin.

4.4.6 Negotiations

The next step in the process involves negotiations. Unless the bidding process calls for a public opening and award based on low price, commercial bidding more typically results in the selection of a short list of bidders for further negotiations. This short list can be as few as one, and is typically two or three, namely a primary candidate, with one or two back-up bidders. There are several reasons for having more than one bidder involved during the negotiation stage. The first is to provide a back up in the event that the negotiations with the primary candidate reach an impasse on some issues, or that in the course of the negotiations, hidden issues cause the real price to rise or the bid to become less desirable than originally presented. It is also possible that because of other business opportunities, (the shipyards may be bidding on several other projects) the primary bidder may withdraw its bid.

A second reason for having back-up bidders is that it is important from a psychological point of view. If the negotiating efforts are to further reduce price or improve terms, it is helpful to the buyer for the primary bidder to know that his competitors are *waiting in the wings.*

In a buyer's market, the buyer must use his advantages judiciously, and not push the bidders below a level of fairness or reasonable profitability. Of course, it is difficult for the buyer to know at what point in the negotiations the bidder reaches a non-compensatory price. Therefore, it is in the buyer's own interest to enter into the negotiations carefully prepared with as much knowledge of not only what he can afford to pay, but also with a knowledge of, or best estimate of the bidder's cost factors, including worker wage rates, projected inflation allowances, worker productivity (such as man-hours required per ton of steel produced or per compensated gross ton), the steel of ship (both plate and shape; both mild and special steels), steel and main engine prices, etc.

The pitfalls in pushing the bidder below a point of reasonable profitability and more importantly into a loss-making contract include the possibility that the bidder will bankrupt itself during the project, or that the candidate may attempt to find ways, during the construction, to reduce the quality or performance of the ship or otherwise avoid its contractual obligations. The probability of dissatisfaction and litigation during or at the end of the project increases dramatically as the losses of the builder increase. The buyer is certainly not responsible for errors, which the builder may make in preparing his bid price or for unforeseen cost increases, which occur during the project. However, he does play an important role in assuring that all participants in the project emerge with a commercially satisfying result at the end of the project.

The negotiations usually dwell on the contract terms (price, delivery and guarantees) and on the specifications.

4.4.7 Ship Financing

There are four principal sources of funds for shipbuilding, namely:

1. debt
2. leasing
3. equity, and
4. government grants.

Within these four categories, there exist a great number of variations and combinations. While the commercial bank loan (debt instrument) remains the classical method for financing ships, there have been major changes over the last two decades in this traditional method. First, the availability of government grants through direct and indirect subsidies, guarantees, etc. has declined. Second, the use of equity markets has grown steadily.

Factors which affect which type of financing to seek, include:

- availability of funds in each finance sector, which can vary cyclically,
- availability of unused tax depreciation suggests leasing,
- companies with excess debt (that is, *all borrowed up)* or which are potential business risks suggest equity,
- buyer's market (shipyard or export credit).
- companies with large earning power, strong predictable cash flows, asset quality and financial leverage below optimal capital structure suggest debt financing, and
- companies whose stock price is extremely low, given future expectations may consider hybrid schemes.

(see Chapter 7 - Mission and Owner's Requirements)

4.4.7.1 Debt financing

Debt financing is the least expensive, but most restrictive form of ship finance. The more usual way to finance ships is through commercial or government loans. These traditional loans are almost always secured or collateralized. The shipowner, in addition to granting a mortgage to the bank on the vessel, may also pledge one or more of the following as collateral:

- assignment of earnings,
- insurance proceeds,
- corporate guarantees,
- pledge of shares, and
- personal guarantees.

Lending institutions seldom lend more than 90 percent of the vessel acquisition or building cost. They prefer to have a portion of the cost provided by the shipowner. There are two reasons for this. First, it ensures a more serious involvement by the shipowner when he has his funds invested. Second, the lender is more likely to recover his full investment in the event of a liquidation of the assets. In the event that the primary lender does not make available sufficient funds, the shipowner may find a second lender who will accept a second mortgage (one that is inferior in rank; that is, which is paid out only after the first mortgage, in the event of liquidation.)

The ship mortgage serves several purposes; namely it provides a public record of the lien on the vessel, the degree to which the vessel is subject to prior liens and the priority of the lien. It also is the basis for an agreement between the lender and the shipowner concerning operation, maintenance, insurance, and trading areas, etc.

Loans can be made on a fixed interest rate basis or a floating or variable rate. Fixed rates from commercial banks are rare since they depend on sources of funds that are themselves subject to variable interest rates. One method of arranging for a fixed rate is to have the lender arrange a *swap,* which is an agreement with a third, party to exchange streams of interest payments. The two parties, which respectively have excess funds at variable and fixed rates, are able to achieve a balance. Such swaps will cost the borrower a higher rate than he would pay for a variable rate.

Another way for a borrower to protect himself against rising interest rates is to pay the bank an extra cost to provide a *cap.* A cap is an agreement by the lender to pay all interest exceeding a certain specified level.

Another form of debt financing is the issuance of bonds by the shipowner, such shipbuilding bonds being certificates of indebtedness for long term loans for a specific purpose, with specified interest rate and payback terms.

4.4.7.2 Leasing

Leasing is a method for increasing assets without equity input from shareholders. It is also a method for a shipowner to trade away tax advantages, such as depreciation, which he is unable to use.

There are two types of leases, *operating* and *finance* leases. The ship-operating lease is a time or voyage charter whereas with a finance lease, the lessor is only responsible for finance; the lessee is responsible for insurance and all operating costs; that is, a *bareboat* lease.

Most new ship leases are leveraged leases where investors provide funds (equity portion) for a portion of the ship's cost and the debt portion is secured by a mortgage and assignment of lease payments. Lease payments cover the debt service and a return to the investors, who also may receive tax benefits and a residual portion of the vessel at the end of the lease.

4.4.7.3 Equity financing

Another source of financing funds is from equity (equity in the sense of shipownership in or shares in the profits or future value of a business).

Hence equity funds for ship acquisition might come from:

- retained earnings,
- cash flow,
- sale of assets,
- sale of stock,
  a. Preferred,
  b. Common, and
- limited partnerships.

The sale of stock to the initial public offerings (lPOs) is a difficult and complex undertaking and becomes realistic only with larger ship owning companies or in large ship acquisition transactions. In most countries, the sale of securities is controlled by strict laws, for example, in the U.S. the Securities and Exchange Commission (SEC) requires rigorous accounting methods (GAAP - generally accepted accounting procedures), disclosure requirements, etc. The floating of a stock issue is expensive, time consuming and requires government review and approval. Nevertheless, many shipowners, particularly tanker and cruise line shipowners resort to this opportunity.

A second method of selling shares for shipbuilding finance is through the private placement market; that is, to such institutions as property and casualty insurance companies, private and public sector pension funds, mutual funds, and finance companies. The funds available in the private placement market are enormous. The key to access to this market is for a shipowner to find an agent or advisor with a strong record of success in this field, and to gain acceptable credit ratings for the shipping transactions being put forward.

4.4.7.4 Government grants

Financing assistance from government sources is done to aid and stimulate domestic shipbuilding or domestic shipping. Such assistance takes many forms and these include, but are not limited to:

- government loans,
- subsidizing interest rate,
- cash grant to shipowner,
- cash grant to shipbuilder,
- cash or credit to allied industries,
- operating subsidies tied to shipbuilding agreement,
- favorable taxation incentives
  a. lower or no taxes,
  b. deferrals,
  c. write-offs,
  d. accelerated depreciation, and
  e. tax-free reserves.
- guarantee of private loans,
- favorable loan terms
  a. low interest rate,
  b. long grace period,
  c. little or no down payment,
  d. more than 40 percent financing,
  e. repayment out of profits only,
  f. long loan term,
  g. balloon payment at end of loan, and
  h. little or no security required.
- write-off of previous losses,
- moratoria on debt repayment,
- training funds,
- custom duties waived on imported materials,
- shipbuilding research and development funds, and
- vessel scrapping subsidies.

4.4.8 Hybrid Schemes

There are a number of hybrid ship finance schemes, which do not fit under the simple debt or equity categories. These methods work for companies whose stock prices are extremely low, given future expectations. They include:

Shipbuilding contracts are *expressed contracts* (stated in writing or orally) rather than *implied contracts.* They are *bilateral contracts,* where both parties mutually promise, one to build and deliver a vessel and the other to pay.

In order to form a valid contract, several other elements are necessary.

They include:

- the parties must be competent,
- the parties must express definite assent in the form required by law,
- at the time of contract, it must not be impossible of performance, and
- it must not contravene law or public policy.

In a multiple ship order, it is customary to have a separate contract for each ship.

The written contract may take one of several forms, namely:

- a specially drafted contract for the transaction by the shipowner's or builder's attorneys. Such contracts usually are biased in the direction of the party preparing the first draft. The party preparing the first draft of course bears the legal expense of such an effort. Also, in some jurisdictions the court places a burden on the party preparing the first draft.
- the shipowner's or builder's usual form of contract. Where either party frequently enters into shipbuilding contracts, they may have a form of contract, which they customarily use, but which should be carefully reviewed by that party's attorneys for applicability to the current types of ships, locale of yard, and/or recent regulations or legal rulings.
- a shipbuilding standard contract form. There are several in common use, namely:
  a. SAJ Form - The Shipowners Association of Japan Form of January 1974.
  b. AWES Form - The Association of West European Shipbuilders Form of July 1972.
  c. MarAd Form - The U.S. Department of Transportation, Maritime Administration, Marine Subsidy Board - 1980.
  d. Norwegian Form - The Association of Norwegian Marine Yards and the Norwegian Shipowner's Association Form of October 1981.

Regardless of which form is used, any shipbuilding contract should contain a number of basic elements. These include:

- identification of the parties,
- description of what is to be done,
- price,
- delivery,
- guarantees,
- test,
- procedures for changes,
- right of rejection,
- default,
- title, and
- legal jurisdiction and dispute resolution.

A shipbuilding contract should identify the shipyard in which the ship will be built. Most contracts do, but the SAJ is silent on this point. The shipowner wants to be assured that the ship will be built in the yard he reviewed and selected.

The contract should state the builder's hull number, and most do, because the shipowner wants assurance that the builder will not substitute a later order ahead of his.

The contract should describe the vessel, even if briefly, including the type, the principal dimensions, registry and classification. A more detailed description is included in the specifications and contract drawings, which should be made a part of the contract.

An important part of the contract should deal with the shipowner's right to inspect the vessel and approve drawings, appointment and rights of shipowner's representative and facilities for them to be provided by the shipyard.

Every contract provides for guaranteed speed, fuel consumption and deadweight tonnage. Some contracts also include a guaranteed cubic capacity (AWES and Norwegian Form). It is not out of order to require the builder to guarantee other features of the ship such as cargo deck area, vertical center of gravity, LNG boil off rate, pallet capacity, lane-meter of vehicle space, number of passenger berths, etc.

The guarantee section ascribes penalties for shortfall, and the right to cancel the contract if the deficiency exceeds a given amount.

The contract will provide a delivery date, an effective starting date, and penalties for late delivery. AWES provide for premiums for early delivery, although most shipowners elect not to include such a clause.

The contract will state the contract price, currency in which payment is made payment methods, installment payments and procedures for extra costs. Provisions may also be made for escalations in the contract price based on wage and/or material cost increases. Generally such escalation clauses, where they do occur, are tied to industrial or governmental indices.

Force majeure terms are usually the subject of much discussion. Some *force majeure* clauses remain among the most arcane to be found in law, for example, *restraint of* *princes, letters of marque,* etc. Nevertheless, other terms are very important and have a reasonable likelihood of occurrence, for example *strikes, riots, civil commotion, earthquakes, hurricanes, floods,* etc. It is reasonable to include events, which are totally out of the control of the shipbuilder. However, shipyards will often ask that clauses referring to *failure of suppliers to deliver materials on time,* be included. It is not in the shipowner's interest to include such a clause since it relieves the yard from a penalty for poor planning; that is, lateness in ordering material, or failure to press the suppliers for timely deliveries.

Liquidated damages for late delivery should not be set so high that they *make the shipowner whole,* but they should be at least high enough to create an incentive for the builder to rectify his lateness, and to compensate the shipowner for interest on his progress payments.

4.5 PRODUCTION

4.5.1 Introduction

The fourth phase in the ship acquisition process involves *Production.* Immediately following the signing of the contract, the initiative in the process shifts from the buyer (shipowner) to the seller (shipyard). While the center of effort lies with the yard, nevertheless, there are a number of important tasks, which a prudent shipowner must carry out or participate in during construction and immediately after delivery. These include:

- shipowner representation/contract management,
- inspection/quality control,
- plan approval,
- crewing, storing and fueling,
- delivery/acceptance protocol, and
- positioning.

The contract should clearly spell out the responsibilities and rights of both parties during this production phase. Even greater detail, in this regard, is often included in the shipbuilding specifications. It is essential that all parties who have responsibilities should be familiar with the terms and details of the contract and specifications. It often has been found useful to extract those portions of each, which apply to them, and distribute these to members of the shipowner's inspection team.

The shipowner has a number of obligations under the shipbuilding contract. In order to handle these duties in an orderly manner, it is customary for the shipowner to appoint a Shipowner's Representative. It is usual for the shipowner's representative to be domiciled for the duration of the project at the shipyard, or lead yard in the case of a multi-yard project.

The duties of the shipowner's representative usually include:

- represent the interests of the shipowner,
- endeavor to keep the project on budget,
- endeavor to keep the project on schedule,
- supervise the inspection team,
- monitor the construction progress,
- assure safe and healthy working conditions for shipowner's staff,
- control and approve the change order process,
- receive, analyze and report to the shipowner progress against schedule,
- identify, report on, and to the extent possible, resolve production problems,
- monitor and record conditions, which may be used as a basis for *force majeure* claims,
- look after the welfare of the inspection team and other shipowner's employees on site including assisting in housing, transportation, visas, taxes, finances, insurance, medical issues, repatriation, replacement, training, etc.,
- manage the field office and its staff including secretarial! clerical staff, office equipment, furniture, computers, communications, petty cash, expense accounts, vehicles, etc.,
- monitor the inspection of workmanship, materials, tests, and trials,
- monitor the yard's quality, quality assurance and safety programs,
- maintain custody of test instruments,
- confirm that the shipyard has met payment milestones,
- assure that shipowner-furnished equipment and supplies are received, inventoried, stored, and protected in warehouses before placement on board,
- coordinate with or supervise the plan approval team,
- coordinate with shipowner's finance, insurance, legal, personnel, and operations departments,
- assist shipowner's marketing, sales, and public relations departments concerning press releases, ceremonies, visits, display models, photos, etc.,
- coordinate crewing and crew-related requirements at the shipyard,
- assist in the initial storing and fueling of the ship, including lubricants and lube oil.
- coordinate with the shipyard's guarantee engineer, after delivery,
- assure that all documents and certificates are provided by the yard,
- accept delivery of the ship on behalf of the shipowner, and

- provide for an orderly shut down of the project, including resolution and closing of accounts, repatriation of crew, organizing and shipping of files, plans and documents, and providing a written summary of the project.

4.5.2 Shipowner Plan Approval

The term *plan approval* in the shipbuilding process refers to the shipowner's review of detailed drawings, calculations, field sketches, test agendas and results, vendor drawings, purchase orders and other technical documentation developed during construction. The principal activity relates to a review of working drawings, which are usually prepared by the shipbuilder's engineering department.

A significant difference between the concept, preliminary and contract design work, on one hand, which we may call the basic design and the detailed design on the other hand, is that the engineering work in the former case may be regarded as developmental and may be subject to constant change and improvement. The engineers preparing the detailed design must make sure that their work conforms to the contract drawings and not make changes, except in strict accordance with the change procedures in the contract.

The detailed design and engineering work that the shipbuilder is responsible for and which the shipowner may review includes some or all of the following:

- working plans,
- finished drawings,
- posted plans,
- vendor drawings,
- field sketches,
- shop drawings,
- schematics,
- drawing changes,
- operating manuals,
- safety manuals,
- maintenance, repair and trouble shooting manuals,
- test agenda,
- test result analyses,
- technical specifications for component procurement,
- *As Built* drawings, and
- training manuals.

In the process of development of the detailed design, or to suit differing yard standards or procedures, the yard may find it necessary or desirable to modify the contract design. This should be done only with the approval ofthe shipowner and in accordance with the contract procedures. It is the responsibility of the builder to obtain regulatory body and classification society approval for such changes.

The right to review detailed drawings is usually reserved under the shipbuilding contract, both explicitly and implicitly. Implicitly, because the shipowner reserves the right to inspect all work in progress, and engineering work is in~cluded in this. Explicitly, because both parties to the contract find it useful to articulate the entire drawing review process.

The plan review usually calls for multiple copies of the detailed plans and other documents to be sent to the shipowner or his naval architect. The receipt and handling of such drawings should be carried out formally and carefully, since the shipowner's responses, and in some cases, failure to respond may have cost, delivery, warranty and legal implications.

There can be as many as one thousand first issue draw~ings developed prior to or during construction. It is useful at the outset for the shipowner or his naval architect to review the proposed plan list and identify those drawings, which he wants to approve, or which he wants only for information purposes.

It is customary for the shipowner to receive all revisions to the first issue drawings also, for approval or re-approval.

The purpose of the plan approval is not to improve upon the design or continue its development. This may occur naturally, but it is not why the procedure is included in the ship acquisition process. The purpose is to assure that the shipbuilder complies with the terms and intent of the contract when details to the design are developed. In the course of the preparation of details, ways to improve the design may occur to the shipowner, or changes in his requirements may suggest modifications to the design. However, these must be regarded as changes under the contract and may result in increases or decreases in contract price and/or changes in the delivery date. Such changes requested by the shipowner may also result in a lessening in the liability of the builder or a diminishment of his warranties, depending on how the changes are requested.

In the course of making comment on drawings under review, the shipowner's comments sometimes might unintentionally be regarded as requests for changes. It is therefore important that the contract (or specifications) include a clause requiring the builder to call the shipowner's attention to the fact that he regards such comments as requests for changes, and state what cost or delivery implications such changes would have.

Transmittal letters should accompany the receipt and return of reviewed drawings. At the very least such transmittal letters establish a time record, since certain of the shipowner's rights to review are usually limited to a certain number of days. This drawing review period is subject to agreement between the parties and is recited in the contract. It is a certain number of days, usually somewhere between 10 and 21 days. It will depend on where the plan reviewer or reviewers are located; that is, at the shipowner's offices, the naval architect's offices, or the shipowner's field office in the shipyard, the complexity of the design, the shipowner's need to review some drawings with the operating department or potential charters, the ship delivery schedule, etc. The period is usually based on date of receipt by the shipowner, date of returning by the shipowner, and the intervening number of working days. A typical contract clause might read:

> The CONTRACTOR shall send to the PURCHASER, or its authorized representative, for approval three copies of the drawings and the technical information for machinery and equipment, for which such approval is required by the Specification(s). One of the three copies so submitted shall be returned, either approved, or supplemented with remarks and amendments, to reach the CONTRACTOR within 14 days from the date of receipt by the PURCHASER or within 21 days after dispatch by the CONTRACTOR, whichever is the shorter, and if this is not done within this time limit the drawings and technical information shall be regarded as approved, unless additional time is specifically requested in writing by the PURCHASER and agreed in writing by the CONTRACTOR.
>
> If the drawings and technical information are returned to the CONTRACTOR within the said time limit supplemented with remarks and amendments by the PURCHASER and if the said remarks and amendments are not of such a nature or extent as to constitute modifications under Article 3 hereof, then the CONTRACTOR shall start or continue production on the corrected or amended drawings and technical information provided that if such remarks and amendments are not clearly specified or detailed. The CONTRACTOR shall be entitled to place its own interpretation on such remarks and amendments in implementing the same.

It is also possible, in the interest of saving time, that field changes, sketches, test memoranda, calculations may be sent and returned by facsimile or bye-mail.

With the advent of computer-aided design (CAD) drawings, it is possible to store, reproduce, and transmit such digitized drawings electronically. The storage of technical information can be made on CD-ROM, hard drives, floppy discs, and other devices.

Some classification societies (ABS and Lloyd's Register) currently, are prepared to receive drawings in electronic format, review them on screen, store and return marked-up drawings electronically; that is, without resorting to paper. Within the near future, shipowners and/or their naval architects should be able to do the same. This should lead to increased accuracy, improved documentation, and a shortening in the time required for review ..

When the naval architect or shipowner's new shipbuilding department is carrying out the plan review, it is important that they coordinate the ideas and needs of the various other shipowner's departments, particularly marine operations. Other interested departments may include sales, purchasing, stevedoring, insurance, safety, chartering, etc.

In reviewing drawings, a number of factors and objectives should be kept in mind. These would include:

- do the drawings comply with the contact?
- does the design meet regulatory body requirements?
- does the design meet classification society rules?
- is the design "first class" and does it reflect "good workmanship."
- does the design reflect modem practice?
- is the design safe?
- have human factors and ergonomics been considered?
- does the design have the appropriate features to protect the environment?
- is the equipment maintainable?
- is the structure or equipment accessible for inspection, maintenance or repair?
- is there continuity of structure?
- is the structure aligned, configured and sized to resist the loads?
- have margins and safety factors been used and are they sufficient?
- are structural butts, seams and joints clear of highly stressed areas?
- has compensation been allowed for cutouts and other apertures?
- is the design free of stress concentrations?
- have the correct welding symbols and materials been designated?
- are the correct materials and alloys called for and are they compatible?
- has drainage been provided?
- are there ladders, scaffolds, or platforms, or other provisions for frequently inspected or maintained equipment?
- will the accidental release of liquids (water, oil, etc.) from pipes, joints, tanks, overflows, etc., spray or flow onto electrical equipment, hot components or otherwise cause a problem?
- are the quarters, working and public spaces habitable, sanitary, maintainable and comfortable?
- do the design and details meet the company's standards?
- are the equipment and its components interchangeable with other equipment in the fleet?

- are all corrections and changes clearly marked?
- are penetrations in watertight bulkheads and decks sound and watertight themselves?
- are the pipes passing through watertight boundaries fitted with non-return valves, where appropriate?
- are the ballast and fuel tank vent pipes, vent heads and the absence of paint on the flame screen adequate to prevent over-pressuring tanks?
- are pressure vessels, pipes and equipment under pressure fitted with the correct appliances?
- are the ship's structure and fittings, and particularly the bottom and forward structure substantial enough to resist slamming, plunging, boarding seas, etc?
- are the quarters, equipment, structure and personnel protected, where appropriate, against ice, snow, rain, sand, wind, waves, sunlight, heat, moisture, noise, and other environmental factors?
- are the drawings correctly labeled, dimensioned to the correct scale, complete, corrected, numbered, dated, signed and contain sufficient and correct references? and
- can the ship or its features be made esthetically pleasing at no additional or at an acceptable level of cost?

It is customary for a shipyard to incorporate many repetitive details into the working drawings. These are usually printed into a booklet of yard standards. They may be separated into booklets of structural details, piping, electrical, HVAC, furniture, etc. These standards may vary considerably from yard to yard. Therefore, it is essential that the shipowner closely examine the yard standards prior to contract. He may not see them again until they are built into the ship, as the working drawings may not show them, but merely incorporate them by reference.

4.5.3 Inspection

Under the terms of virtually all shipbuilding construction contracts, the shipowner reserves the right to carry out inspections of the work in progress and to witness tests and trials.

The specifications are often more explicit in the inspection procedures which are to be followed.

The purpose of shipbuilding inspection by the shipowner is to assure that the vessel is constructed in accordance with the contract plans and specifications, and that the workmanship and materials meet the intent of the contract.

It is intended that the scope of the shipowner's inspection program be unrestricted by the shipbuilder, that free and ready access is provided, and that it covers all materials and work entering into the construction. It may extend, at the shipowner's option, to every detail in the ship. It includes all aspects of safety, economy, efficiency, maintainability, habitability, esthetics, etc. Shipowners should not confuse the roles played by classification society and governmental inspectors with that ofthe shipowner's inspectors. Some shipowners are shortsighted enough to forego their right to inspect the vessel and defer to do the class and regulatory inspections. Obviously, the latter bodies have no responsibility for and very little knowledge of the commercial interests of the shipowner and are focused on safety issues. Matters such as life of coatings, the appearance of the ship (style), the comfort ofthe crew, the cost of operation ofthe ship, the speed of cargo handling equipment, etc. are matters which are of vital concern to the shipowner, and which are beyond the scope of classification and regulatory body inspection. Furthermore, U.S. courts have held that a shipowner cannot delegate the responsibility for assuring that his ship is seaworthy.

Most shipyards have *quality control, quality assurance* and/or *quality* programs in place. Such programs are intended to produce ships, which meet the intended level of quality defined by the contract and specifications. Ideally, the builder would, because of his quality programs, deliver a ship free of defects. Unfortunately, some such quality programs contain defects. It is apparent that there must be a series of *safety nets,* commencing with the builder's quality control; and including the shipowner's inspection team, the classification society and the regulatory bodies; that is, flag state control. In some cases such as passenger ships, tankers, gas carriers, an additional safety net, in the form of port state control exists, particularly in the U.S. with foreign flag vessels trading to U.S. ports.

Another reason for the shipowner to have his inspectors in place is because not every detail of construction is, nor or need be, shown on the drawings which are sent to the shipowner for approval. However, often, the small details, which emerge on the scene, are of great importance to the shipowner, and may affect his operations.

During the construction process, it is commonplace, for reasons of improved efficiency, for field changes to be made. These may apply to fasteners, brackets, arrangements, etc. The local inspectors can approve these field changes, ifthey are not of a significant technical nature. However, the plan approval agent should be advised of such field changes to assure that there is not conflict with other plans or processes.

4.5.3.1 Hull inspection

The hull inspector's responsibility is the structure of the ship. On a very large project, a welding inspector would assist the hull inspector. On small jobs, the hull inspector may also handle coatings, deck machinery, superstructure outfitting and other duties. Regardless of the size of the project, a ship's new construction team will always have at least one hull or structural inspector. Large, complex or multi-ship projects may have more than one hull inspector and might also have a welding inspector.

It is the responsibility of the hull inspector to inspect and follow the progress ofthe fabrication of the ship's structure. This work commences upon the arrival of steel plate and shapes (profiles) at the yard. It continues as the steel, or other materials such as aluminum, wood, plastic, etc., is prepared (straightened, dried, blasted, primed and marked) for cutting, forming and joining.

The hull inspector follows the structure through the fabrication shops; that is, plate shop (two dimension), and block shop (three-dimension) and at the platens.

The hull inspector will continue to follow the blocks into the building (graving) dock or onto the launching ways, where they are assembled into the ship. His work continues through launching and trials to delivery.

4.5.3.2 Welding inspection

A welding inspector (in the event that if there is no welding inspector, then the hull inspector), shall ensure that:

- the types and sizes of welds, and the edge preparation are appropriate and correct for the application,
- welding sequences are proper and do not create locked in stresses or deformations.
- all structure is properly aligned and spaced before weldmg,
- welding is carried out in accordance with agreed upon standards, codes and good practice, especially with regard to absence of spatter, porosity, undercutting, strikes, excessive crown, cracks and other irregularities,
- welding rods are of the correct type and are kept in a dry environment,
- selection of welds, castings and forgings to be specially inspected by non-destructive test methods or for tensile, impact or fatigue tests,
- witnessing tests and results of radiographic (x-rays), magnetic particle, ultrasonic, and dye penetrant tests, and
- assist the hull inspectors, as required.

4.5.3.3 Coating inspection

On small projects the structural inspector may handle coating inspection. However, on larger projects a coating specialist may be engaged, as part of the inspection team to carry out this work. In some cases, the coating (paint) supplier will give guarantees of five years or more for his paint. Since the effectiveness of such systems is highly dependent on the surface preparation, environmental conditions during application and thickness of the application, close supervision and monitoring is necessary if such long guarantees are given. Therefore, often the paint manufacturer will have his representative on site. Nevertheless, on large projects, assignment of a shipowner's coating inspector is prudent.

The test instruments most useful to the coatings inspector range from the simple thermometer, hygrometer and anemometer and wet thickness gauge, to more sophisticated electronic dry thickness measurement devices, surface profilers, etc.

Many factors have emerged in recent years to make the assurance of correct coatings vital to the shipowner. These include:

- the desire for extended dry-docking periods (5 years),
- the high cost of recleaning and recoating,
- the reduction in crew size and unavailability of personnel to perform onboard chipping and painting,
- fast port and shipyard turnaround, inhibiting the use of shore side coating workers,
- the sheer size of many ships, especially VLCCs and ULCCs,
- the never-empty nature of containerships, inhibiting access to cargo hold,
- the use of high strength steels (HTS), whose corrosion rates are the same as thicker mild steel structures, and hence waste away soone, and
- the reduction in structural design safety margins, and use of computers resulting in smaller scantlings, which are subject to more rapid wastage.

One should refer to ASTM F 1130-93, Standard Practice for Inspecting the Coating System of a Ship. Hence, it behooves the shipowner to give very careful attention to the selection of a good coating manufacturer, proper coatings, an effective specification, a long guarantee and good inspection.

4.5.3.4 Electrical inspection

The electrical inspector is generally responsible for the inspection and witnessing of tests for the following:

- electrical generators,
- switchgear, switchboards, distribution panels and associated instrumentation,
- transformers, regulators, circuit breakers, synchronizing equipment,
- motors, brakes, electric clutches,
- wiring, buses, wireways, wire, and cable penetrations,
- lighting,
- electronic equipment,
- communication equipment,
- automation systems,

- impressed current system,
- electrical insulation,
- monitors, sensors, alarms, annunciators,
- antennae, wave guides, transducers,
- electrical and communication shore connections,
- computers and their networks, and
- fiber optic systems.

Because of rapid advances in electronic equipment, especially computers and automation equipment and the difficulty in finding electrical inspectors with expertise in both electrical and electronic fields, it is sometimes necessary to split the tasks between two specialists, one electrical and the other electronic.

4.5.3.5 Machinery inspection

Machinery inspectors are required to inspect and witness the testing of all mechanical, hydraulic, and pneumatic equipment and their related instrumentation. These include, but are not limited to:

- main propulsion machinery,
- shafting, bearings and propeller,
- auxiliary electrical generators,
- heating, ventilation, and air conditioning,
- refrigeration and dehumidification,
- rudders and steering gear,
- cargo handling equipment,
- auxiliary machinery, and
- deck machinery.

In addition to assuring that such equipment is correctly installed and connected to other systems, the inspectors must assure that such equipment and systems:

- are assembled correctly,
- are installed according to the manufacturers instructions and good practice,
- are arranged to provide safe access for operation and maintenance,
- sufficient room is left for opening, inspection and/or removal,
- the equipment is not a hazard, through malfunction to equipment in its vicinity,
- the foundations are appropriate for the equipment,
- the equipment has the correct size or capacity for the service intended,
- the equipment is free of abnormal vibrations,
- the equipment does not generate abnormal noise,
- the equipment or systems are environmentally sound especially with respect to oil spill, solid waste, or sewage water pollution, air pollution, toxic fume generation, excessive noise, etc.,
- the systems are energy efficient,
- the equipment is user friendly, properly marked and pf9-vided with instruction books, operating guides, trouble shooting information, parts lists, etc., and
- the machinery and equipment meets performance specifications.

It is generally accepted that effective shipbuilding machinery inspectors are former ships' engineers (usually chief engineers) who have a specialty in the type equipment being installed, such as steam, diesel or gas turbine propulsion plans. Where possible, it is useful to have machinery inspectors who have taken various manufacturers' training courses.

It is customary to have the machinery inspectors' work very closely with the vessels' chief engineer, who usually arrives on site later in the program. Often, one of the shipowner's senior chief engineer's is assigned to the lead ship and may arrive at the yard early in the construction program (such as when the main engine is on the test bed at the engine plant).

4.5.4 Test and Trials

One of the most critical periods during the production period, and one where the shipowner bears important responsibilities involves tests and trials. Testing occurs throughout the entire construction period. It begins with testing the basic materials, for example, classification surveyors testing hull steel at the steel mills, or castings and forgings, or with machinery manufacturers testing and demonstrating their machinery on test beds at the factory, and continues through the construction period at the shipyard, culminating with the successful completion of sea trials.

Classification society surveyors, regulatory body inspectors, and/or shipowner representatives, may witness the tests. In some jurisdictions, the failure of the shipowner to participate in certain tests may invalidate future claims against the builder.

Since testing and trials are usually disruptive to the construction process, it is essential that they be well planned and scheduled. The shipowner and his representatives should be cooperative in this process.

Many tests are prescribed in classification society rules or governmental regulations. The builder and his quality control department will routinely have his schedule of tests. Additionally, the shipowner should include in the specifications any other tests he may require.

These should be described in detail or by reference to industry test standards, such as SNAME, ASTM, ASME, ASHRAE, IEEE, together with the test number and date of issue, etc. Where the shipowner may require such special tests, he should be prepared to provide copies or be able to direct the shipbuilders to sources for the latest editions of these, before the time of contract.

The more important tests should be described in detail. For example, a containership shipowner will be interested in stability and, therefore, the inclining test should receive particular attention. The passenger shipowner may focus on noise and vibration tests, the gas carrier on the gas trials, the reefer shipowner on insulation and refrigeration tests, etc.

In most cases, failure to meet certain important tests will be keyed to penalty or cancellation clauses in the contract. Therefore, it is of extreme importance that the tests be very carefully and completely described. Pass-fail criteria must be included. In the event of disputes concerning the conduct of the tests or the results, many contracts will contain simplified dispute resolution clauses.

It is customary for the shipbuilder to prepare a test schedule early in the production program. The schedule will include the components or systems being tested, projected starting and completion dates. This schedule is useful to the shipowner's representative in planning his manpower requirements. It also serves as a measure of the progress of the completion of the 'ship. Test memoranda or procedures are prepared and agreed to, describing the tests to be carried out for each component or system. These memoranda include such information as:

- applicable drawings,
- design and performance data,
- pass-fail criteria,
- pre-test inspection procedure,
- detailed procedure to conducting the test,
- forms for recording test and results, and
- post-test procedures.

The principal tests in a shipbuilding program include:

- material tests - physical and chemical,
- shop trials - components (see SNAME T&R Bulletin 308 *Code on Installation and Shop Trials,)*
- welder qualification-classification society,
- welding - destructive and non-destructive,
- piping - pressure, temperature, flow, etc.,
- electrical - voltage, resistance, grounds, etc.,
- pressure vessels - pressure,
- instrumentation - calibration,
- machinery and components - performance,
- lighting equipment - performance and load,
- HVAC - flow, temperature, humidity, etc.,
- lighting - light levels,
- container cell guide clearances and reefer container power and monitoring systems,
- hatch cover operation and tightness,
- for LNG, gas trials,
- for reefer ships, refrigeration, air circulation and insulation tests, and
- hose and/or pressure testing of watertight bulkheads, watertight doors and other closures, tanks and hatch covers to demonstrate tightness and structural adequacy.

Late in the construction program and prior to sea trials, but after all machinery components and systems have been tested, it is customary to carry out dock trials of four to eight hours duration. These are low-power tests conducted with the ship securely restrained at her berth. Care must be exercised before and during dock trials. Damage to the propeller, ingestion of mud and debris, strength of moorings and fittings, and scouring of the berth should be considered when establishing the power levels and propeller RPMs to be tested.

After all construction is complete and all machinery and components are in place and secure, an inclining test is carried out to determine the vessel's vertical center of gravity. All loose gear, debris, garbage, scrap, scaffolding, welding machines, portable blowers and any other material not belonging to the ship must be removed. For the results of an inclining experiment to be valid, there must be no slack liquids in the vessel. Bilges and holds must be dry. Tanks containing liquids must be stripped or pressed up with no voids or air pockets remaining.

During the inclining test, work on the ship is suspended with no workmen, and essentially only a watch and testing personnel on board. Excessive wind can result in inaccurate healing moments. Snow, ice, or standing water from rain will cause inaccuracies. Drafts must be able to be read accurately. The vessel must be freely afloat, away from the dock, and not unduly restrained by its mooring lines. The procedures for conducting an inclining experiment are given in USCG NVIC No. 1-67, or in ASTM F1321-92.

The deadweight survey is a very accurate determination of the lightweight of the ship, conducted in the same manner as above, but without inclining the ship. Drafts are read at multiple stations along each side of the vessel, to determine the deflection of the hull. After accurately allowing for water temperature and salinity, the light ship and deadweight of the ship are determined.

Pre- and post-trial dry docking is usually carried out, especially if the hull has been in the fitting out dock or wet basin after launching, for an extended period of time, or is in a warmer water area. The purpose of the pre trial docking is to assure that the hull and propeller are clean and free of fouling, the intakes are clear, that there are no pits from improperly grounded welding, that the coatings are intact and there was no damage from the launching or dock trialso The post trial drydocking serves the same purpose in addition to assuring that no damage occurred during the sea trials. In multiple ship orders, the pre trial docking may be dispensed with after the delivery of the first vessel.

Sea trials are carried out when the vessel construction is substantially completed (usually one or more weeks before the scheduled delivery), and the dock trials have been performed successfully.

Sea trials involve a large number of people and considerable expense. Therefore, they should be planned and scheduled with great care. The shipowner should be represented by an experienced naval architect and marine engineer, as well as key members of his inspection team. He should also have the designated master and chief engineer on board as observers and for familiarization purposes.

Not every vessel in a multiple ship program needs to undergo every trial test. For example, usually only the first ship in a series will undergo the standardization (speed) trial, the economy (fuel consumption) trial and the collection of data for the maneuvering placard and booklet.

The trials should be conducted in accordance with a well-defined trial agenda. SNAME T&R Bulletin 3-47 Code C-2, *Code for Sea Trials,* is a well-known and widely used guide to the execution of sea trials. SNAME's T&R Bulletin No. 3-17, *Recommended Practices for Steam Power Plan Trial Peiformance,* is another useful document for steam plant trials. Also refer to ISO TC8 *Guidelines for the Assessment Speed and Power Peiformance by Speed Trials.*

Sea trials, which are usually conducted in open, deep water are meant to demonstrate and quantify the vessel's performance (such as steering gear and wind class tests), and to satisfy certain contractual guarantees (such as speed and fuel rate). They are meant to provide useful operational data (such as maneuvering characteristics). Allowances are made for current wind and sea conditions by running reciprocal courses.

The tests that are usually performed include:

- standardization trial - speed trials, establishment of speed/RPM relationships, correlation with model test predictions,
- endurance trials - conducted for four hours to eight hours, unattended (if the vessel is automated) at normal power and four hours at maximum power to demonstrate the performance of the power plant and propulsion system,
- economy trials - to measure the fuel consumption, usually conducted during the endurance trials,
- maneuvering trials - to demonstrate the maneuvering capabilities of the ship, measure its characteristics and to prove the steering gear, rudder and other related machinery. The maneuvering trials include:
  a. turning circles,
  b. Z-maneuver and spiral maneuver,
  c. emergency (crash) stop, full ahead to full astern, and VIce versa,
  d. directional stability,
  e. astern run,
- emergency steering gear tests,
- bow and stem thruster tests,
- anchor windlass tests,
- vibration measurements (see SNAME Code C-I *Code for Shipboard Vibration Measurements,* Code C-4 *Code for Local Structures and Machinery Vibration Measurements,* and Code C-5 *Acceptable Vibration of Marine and Gas Turbine Main and Auxiliary Machinery Plants,)*
- noise measurements,
- compass and radio direction finder calibration, and
- navigation equipment tests, during endurance trials.

A post-trial conference should be conducted while the ship is at sea, at the conclusion of all tests, wherein the shipbuilder should be made aware of all deficiencies observed by the shipowner, class surveyors or regulatory body inspectors. This will give the shipbuilder the opportunity to take corrective actions and re-test the vessel. The questionable performance of any machinery or systems should also be identified at this time.

A formal report of the sea trials results should be provided to the shipowner by the shipbuilder.

4.5.5 Crewing, Storing and Fueling

The initial crewing of the vessel is a shipowner's function and may involve considerable expense and effort. It is obvious that the shipowner will want to minimize the costs associated with this activity. Therefore, he will want to delay the assignment of the officers and unlicensed crew members until the last possible moment, consistent with many other considerations. For this reason, it is essential that the shipowner's representative work very closely with the shipowner's operating department, vessel managers and/or crewing agents to keep them informed of the shipbuilding schedule, and particularly of any factors which may delay delivery of the ship.

While it is customary to assign and position the crew members before delivery for familiarization and training, certain key crew members may be assigned even earlier.

On the other hand, the shipowner may furnish the initial supply offoodstuff, linens, navigation charts, extra spare parts, cleaning materials, and other consumables. He also may elect to furnish portable computers and their software.

If these shipowner-furnished items arrive at the shipyard before the ship is delivered, they must be inventoried and warehoused in a dry, climate-controlled, and secure place before placement on board. Many shipowners find it useful to accumulate, transport, and marshal many of these shipowner's items in sealed, steel intermodal shipping containers.

It may be necessary for the shipyard to put consumable stores on board for the trial trip. It is mutually advantageous for the shipowner and the yard to agree, in advance, for the shipowner to take over appropriate unbroached stores.

Similarly, the vessel will require fuel, lube oil, hydraulic oil, greases, and other lubricants in order for the yard to conduct tests, dock trials, and sea trials. In some cases, for tax reasons, the place of delivery is distant from the yard. This positioning also requires fuel and lube oil. Since the quantities and value of this may be considerable and it is very impractical to remove the yard's fuels and lubricants to replace them with the shipowner's, it is customary for the shipowner to take over, and pay for the fuel and lubes. In this regard, it is important that a very accurate inventory be taken immediately prior to delivery.

Since the fuels and particularly lubes of some manufacturers are incompatible with those of others, the usual practice is for the shipowner to specify to the shipyard which brand of lubricants to be used in the initial charge.

While it is seldom done, it is prudent for the shipowner to ask for a laboratory analysis on the fuel remaining on board at delivery. A spectrographic analysis of the lube oils in the various systems is also useful in establishing baseline condition for future analyses in any predictive maintenance program.

4.5.6 Delivery and Acceptance

This phase of the effort is the *raison d'etre* for the new ship acquisition process. It has many important aspects: logistical, financial, but most important, legal. It should not be executed without proper legal advice and guidance, since many of the seemingly unimportant or trivial tasks and events surrounding it, in fact, have real significance.

The protocol for delivery and acceptance are usually detailed in the shipbuilding contract. The standard forms (AWES, SAJ, MARAD, etc.) are varied in their approach. Custom written shipbuilding contracts tend to be more detailed, as they address the peculiar complexities of the process.

In the U.S., under the Uniform Commercial Code, title passes when the seller completes his performance with reference to the physical delivery of goods, although the buyer may obtain a special right in the ship when the ship is *marked* or identified (as the goods referred to in the contract). In other countries, title may pass when it is in a deliverable state, or when both parties agree, or when the vessel is registered, or when it is physically delivered.

Other complications arise regarding third party rights, ship ownership of shipowner-supplied materials, which are incorporated in the construction or items, owned by the builder, which are not physically part of the ship. It is for these and other reasons that the prudent buyer of a ship will seek the assistance of a lawyer. It is convenient for the shipbuilder and shipowner to agree upon the conditions precedent, and method for the delivery to take place. It is customary for the necessary certificates and documents to be identified in the contract.

4.5.7 Deficiencies and Unfinished Work

While the ship acquisition process mainly involves four principal phases, namely planning, design, commercial and production activities, there does remain a fifth phase which occurs after a vessel or vessels are delivered to the buyer. This last phase involves the completion of outstanding or incomplete work by the shipyard or the correction of defects, which become apparent through inspection or testing. This unfinished work may be of a minor nature or not consequential enough for a shipowner to want to delay taking delivery of the vessel.

It is customary for the inspection team to compile a list of unfinished or incorrect work during the project, and check off various items as they are completed or corrected. Such lists are known by different names, such as *punch lists*, deficiency lists, etc. As the project draws to a close and delivery day nears, the lists of each inspector are merged into a master list. The shipowner's representative must work very closely with the shipyard's project manager to prioritize the items on the list and assure that all work is completed.

It is of considerable importance that nothing should remain on the list, which would affect the seaworthiness, safety, or reliability of the vessel nor impair the vessel from performing its mission.

At the delivery of the vessel, the buyer should take exception to any remaining deficiencies. There should be a clear understanding of the nature of the items, when they will be corrected, where (return to the builder or at a remote yard or by riding gangs while vessel is in service), who will pay for the work and whether any additional compensation is due because of possible disruption to the shipowner's plans. These items, after discussion and agreement between the parties should be reduced to writing and made a part of the delivery protocol.

4.5.8 Temporary and Permanent Documents

It is frequently the case that governmental authorities delay executing the official documents of the vessel. In such cases, governments will issue provisional or temporary certificates. It is the responsibility of the shipyard to deliver the vessel fully documented (there are some exceptions, such as the issuance of a radio license in some countries). Therefore, it is necessary that a designated person in the shipyard monitor and expedite the completion of this work.

In some cases, the shipowner's final payment, typically two or three percent, is withheld until all permanent certificates and other paperwork is completed. This is a harsh but effective procedure in seeing that this remaining work is not ignored.

4.5.9 Warranty

Corley and Roberts (10) define *Warranty* as *"an undertaking, either expressed or implied, that a certain fact regarding subject matter of a contract is presently true or will be true."* The word relates to quality. To warrant is to assure that a state of fact exists. Rothenberg defines a warranty as an agreement to make up for any damages that result from a false representation of the facts. The term guarantee (sometimes spelled *guaranty)* is more explicit, in that it is defined as *"a statement by a producer that his product meets certain standards, and that if it proves defective, he will make restitution. "* Warranty has many meanings, but in the law of the sale of goods it means the obligations of the seller with respect to the goods sold. In the case of ships and their equipment, expressed warranties are provided to the shipowner in the building contract and are given to the shipyard in the purchasing documents by the equipment suppliers. These equipment warranties are transferred to the shipowner at the time of delivery of the ship. Consequential damages or loss of earnings are seldom provided for in expressed warranties.

It is important that the shipowner use every effort, before the signing of the contract, to assure that the yard will obtain vendor warranties that commence at the time of delivery of the ship rather than at the time of delivery of the material at the yard or at time of installation. In the former case, the warranty can nearly run out before the equipment is ever put into service.

During the first months of operation of a vessel, and especially the lead vessel in a series, the majority of failures of equipment will occur. During this intense period of breakdown, claims and repairs, shipowners and shipyards alike have found it useful to assign a guarantee engineer to ride the ship. Since the ship usually will have to be repaired in areas remote from the builder's yard, the guarantee engineer acts as the builder's representative in negotiating and settling repair costs. The guarantee engineer is also in an excellent position to judge the reasonableness of the shipowner's claims. Most warranties are limited to failures under *normal wear and tear.* If the equipment is abused or if the new crew lacks training or skill in operating the machinery and this is the cause for breakdown, the guarantee engineer, is in a position to dispute the claim and document the reasons.'

It is usual for the builder to pay the wages of the guarantee engineer, whereas, the shipowner provides quarters and subsistence aboard ship.

4.5.10 Closing the Project

While this final step is often omitted in ship acquisjtion projects, it is nevertheless an important one and deserves consideration.

There may be a number of open issues at the time of delivery of the ship or last ship in a series. These might include unfinished work, mistakes requiring correction, incomplete or temporary documents, unpaid accounts, unresolved insurance claims, open personnel matters, etc. Some of these items do not need the services of the acquisition team, and can be attended to by the shipowner's administrative or operating personnel. Therefore, it is important that the shipowner's representative provide an orderly and well-documented turnover of all open items to those who will inherit them.

The project manager should settle the question of personnel reassignment or termination. This includes settlement of wages, expense accounts, advances, medical claims, termination of leases, repatriation and similar matters.

The closing of the project office also includes culling and organizing the files. A complete set of construction drawings, calculations, vendors' drawings, progress photographs, certificates, etc. should be indexed and neatly boxed for return to the shipowner's home office.

It has been found to be of great use for the project manager to prepare a project completion report, which should include a summary of the major events and milestones, key progress photos, a summary of the construction costs, and other project costs as measured against the original budget. The closing reports should identify and give credit to personnel who made important contributions to the project.

The report should include a section with recommendations on improvements in the project planning, project design, project procedures, and/or project management. These suggestions can improve the process when the ship acquisition process is repeated.

4.6 CLOSURE

It is clear that in managing the entire ship acquisition process (planning, design, commercial and production) and particularly the shipowner representative functions, that good project management skills are essential. It would greatly benefit the prospective manager by taking a short course or reading a book on project management. The importance of good communication and personnel selection, and proper budgeting and scheduling cannot be overemphasized. The success of the ship acquisition process depends upon it.

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Chapter 5;

The Ship Design Process

Peter A. Gale

5.1 INTRODUCTION

5.1.1 Definition of Design

Design can be defined as the activity involved in producing the drawings (or 3-D computer models), specifications and other data needed to construct an object, in this case a ship. The purpose of this chapter is to describe the process followed in creating a ship design, in full recognition of the fact that the process varies, to some extent, depending on the type of ship being designed and the personal preferences of the design team leaders. It is also true that, as this chapter is written, the design process is being scrutinized, and in some cases modified, with a frequency and intensity never before experienced. This is primarily the result of the opportunities presented by the accelerating advance of computer technology, coupled with the competition of the global marketplace, which causes all enterprises to constantly review their processes with an eye to improving efficiency.

Thus, there is no single ship design process today and the generic, typical process described here will certainly change somewhat in the years to come. What will not change significantly, it is believed, are:

- The objectives of the design process,
- The need for the designer to understand the shipowner's requirements and, at the same time, to help the shipowner to refine his requirements. (See Chapter 7 - Requirements Definition),
- The time and resource constraints imposed on the process,
- The fact that both art and science are reflected in the process (albeit that the role of science is steadily growing at the expense of art), and
- The fact that creativity and teamwork will always be cornerstones of the process.

This chapter covers both naval and commercial ships. Where appropriate the differences are described. However, to do this for every aspect throughout the chapter would have resulted in a very complicated text. It was decided to *take the high road;* that is, the greater level of design involved in naval ships has been described. It should be noted that for most commercial ship designs the clear definition and use of the design phases become blurred and that the design phases omit many of the described steps.

This is only possible, however, for shipyards with good current ship design and construction experience. For commercial ship types that are new to a shipyard or are of high complexity, such as cruise ships, more design phases, phase content and scope will be required and may approach the level applied to naval ships (see references 1 and 2 for typical commercial ship design practice).

5.1.2 Objectives of Design

The primary objective of the design effort, besides creating the information needed to build the ship, is to satisfy the shipowner's requirements at minimum cost. A ship's life cycle cost includes the design, construction, and operating and support (O&S) costs. For designs that incorporate new technologies [and hence research and development (R&D) costs] . and/or significant disposal costs, these also must be included .

One of the responsibilities of the ship designer is to make the shipowner aware of design options that might increase acquisition cost but accrue even greater savings in O&S costs over the ship's life cycle. There are other design objectives as well. The specifications required to test the completed ship and demonstrate that it indeed meets the shipowner's requirements must be developed. Regulatory body and classification society requirements must be satisfied. (See Chapter 8 - Regulatory and Classification Requirements.) Beyond these objectives, the designers must make every effort to create a ship that the shipowner will be pleased with. This means that it must be safe, reliable, and as economical, to operate and maintain as possible, within the constraints imposed by technology and the shipowner's budget.

5.1.3 The Nature of Design

Ship design is an iterative process, especially in the early stages. (See Chapter **11 -** Parametric Design.) The ultimate result is postulated and then analyzed and modified. The modified result is re-analyzed and so on until all requirements are satisfied. The reason for iteration is that ship design has so far proven to be too complex to be described by a set of equations, which can be solved directly. Instead, educated guesses are made as to hull size, displacement, etc. to get the process started and then the initial guesses are modified, as better information becomes available. The design spiral, first described in reference 3, has been used to characterize the design process. Figure 5.1 is one of many possible versions of the characterization. In this visualization, the ship designers' move through the design process in a sequential series of steps, each dealing with a particular synthesis or analysis task. After all the steps have been completed, the design is unlikely to be balanced (or even feasible). Thus a second cycle begins and all the steps are repeated in the same sequence. Typically, a number of cycles (design iterations) are required to arrive at a satisfactory solution. Anyone who has ever participated in a ship design knows that this characterization leaves much to be desired. In practice, the process is not sequential, unless the design is developed entirely by one person. Even then, the steps often will not be perfornled in a prescribed order but rather the naval architect will jump from one spot to another on the spiral, as knowledge is gained and problems are encountered.

In fact, the design process in the early stages is rather unpredictable. Once a baseline concept has been identified and defined in sufficient detail for it to be understood and used by the principal design disciplines, for example, structures, propulsion, electrical, general arrangements, weight estimation, etc., then design work in these principal disciplines will generally proceed in parallel, as shown in Figure 5.2.

For each discipline, a series of tasks must be performed and there is usually a preferred sequence for the tasks. As each task is completed, the products of the task can be shared with the other members of the design team.

This may sound rather orderly. In fact, major problems are identified in the course of design and the act of resolving these problems typically perturbs the design effort in a number of design disciplines, requiring restarts or reworks of tasks previously completed. The number and severity of the problems identified are generally greatest early in design; they tend to decrease in both respects as the design is developed in greater detail.

A major design effort is planned so that formal updates of the design baseline occur at regular intervals. At these milestones, the current hull form and general arrangements are formally issued to the other members of the team and they are directed to shift to these configurations in their subsequent work.

Today, the current configuration is likely to be a 3-D computer model that all design team members have access to by means of a network, but that can only be updated with the approval of the team leader. When a major problem is identified soon after a baseline update, the design team must decide how to approach its resolution and, when a solution has been found, whether to issue an unscheduled baseline update immediately or to wait until the next planned update. The downside of waiting is that additional work will have to be done. The downside of an immediate update is that in some disciplines, the work stop/restart may delay the discovery of another major problem *just around the comer.*

5.1.4 The Design Environment

Ship design takes place within a surrounding environment that can have a significant effect upon the process. Factors in this environment include:

- economic trends,
- current and pending government policies and regulations,
- the status of international regulations on matters such as pollution control,

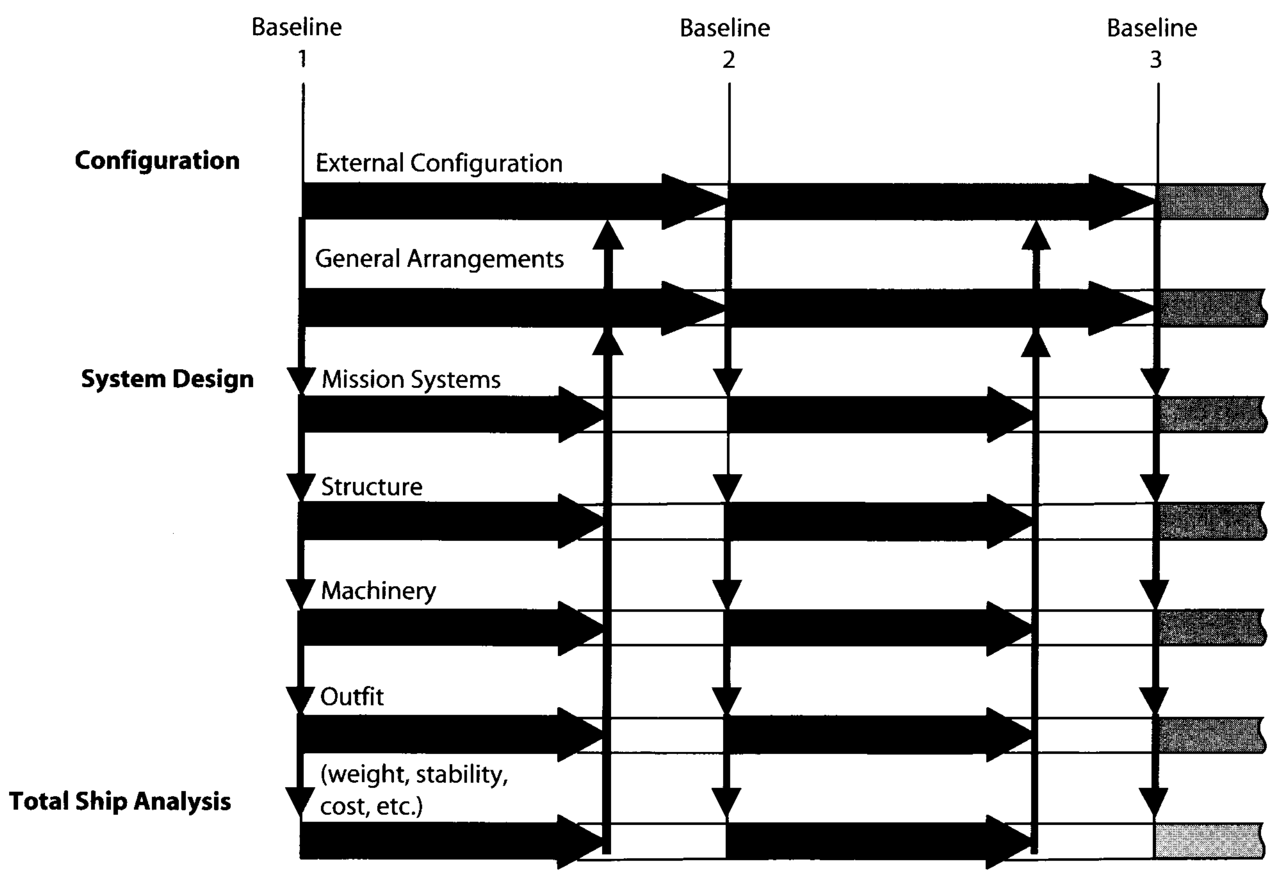

Figure 5.2 Design Development Process

- the breadth and depth of the vendor base for major equipment items,
- the management of the organization within which the design team works and to whom it reports, be that organization a shipyard or a design agent, and
- the prospective shipowner-his foibles, preferences, modus operandi, etc.

For naval and other government ships, additional factors come into play, including the congressional budget process, the terms in office of key decision makers in the Executive Branch and Congress, and political considerations.

Projected economic trends not only affect the viability of a proposed shipbuilding program, but also affect the tradeoff studies and design decisions within the design effort itself. An example is how the projected cost of fuel will affect the decision on propulsion plant type and prime mover. The double hull tanker rules, which resulted from the OPA 90 legislation, are a good example of the impact that pending government regulations can have on ship design.

How will top management interact with the design team? How frequent and how detailed do they want status briefs to be? To what extent do they wish to participate in design decisions? The last three questions apply to the prospective shipowner as well. Good relationships between the design team, the shipowner-to-be and the design team's management can foster mutual understanding, speed up the design process by getting critical design decisions made more quickly, without second guessing, and produce a better product with less stress. Poor relationships between the design team and either of these two groups can cause high stress, burnout and, ultimately, a poorer product.

5.1.5 Design Participants

One person can develop the design for a relatively small, simple ship but typically ship design is a team effort. The team size will generally grow as the design is developed in progressively greater detail. For a small, relatively straightforward ship design, the team size might start at one and ultimately increase to five or six. For a large, complex warship, the design team size might start at 25 to 50 and ultimately grow to many hundreds, assuming that the combat system design integrators are included.

Core team members will always include naval architects, marine engineers and designers with CAD skills for 3-D modeling using the computer. Structural, mechanical, and electrical engineers are also typically represented. Shipyard personnel with expertise in ship construction and production planning are needed, as are equipment vendors with specialized expertise regarding the systems and equipment they offer. Even commercial ship designs may require other specialized expertise, for example, computational fluid dynamics (CFD) analysis, finite element structural analysis (PEA), propeller design, acoustic analysis, reliability analysis, or human factors engineering, which might be obtained via consultants. If the new ship is to be certified by a classification society, liaison with that society is established early in design. Hydrodynamic model testing is still the norm during the pre-contract naval ship design process, but not for commercial ships, and representatives of the selected model basin can provide invaluable assistance to the design team. It is essential that cost analysis expertise be represented on the team; one or more shipowner's representatives are also important team members.

5.1.6 Design Tools

Ship designers rely upon extensive databases for previous designs, together with lessons learned from operational experience with the ships built to those designs. (See Chapter 11 - Parametric Design.) Increasingly, such data is held in the computer, in a form, which is readily accessible and easily manipulated to suit the needs of the designer. The design team uses a myriad of other design tools. These tools generally exist in the form of computer software used to model the ship geometry or perform analyses of various types. (See Chapter 13 - Computer Based Tools.) Increasingly, these ship design and analysis tools are being linked into integrated design systems. These systems can speed up the design process by eliminating much of the time and effort spent moving between individual computer programs that are not efficiently linked. More often, use of these sophisticated systems does not save time but instead permits the designers to explore more alternatives in greater detail in the time available.

5.1.7 Design Standards

Design standards, as the term is used here, refers to a broad category of second tier design, construction, inspection, and/or test requirements which are normally imposed on a new design. They are distinctly different from the *Shipowner's Requirements*, which are typically top-level performance requirements, such as, cargo capacity, speed, and endurance. If the ship is to be classed, the rules of the designated classification society are a form of design standards. There are national and international regulations pertaining to matters such as personnel health and safety, safe navigation, and pollution control. These regulations are a form of design standards. Shipowners with large fleets will typically have design standards of their own. For example, a shipowner might specify the use of a certain propulsion prime mover to achieve standardization within his fleet. Government agencies such as the U.S. Navy, NOAA and the U.S. Coast Guard have standards or preferences that they apply to designs for new ships that they will operate. Design standards, as defined previously, can have a significant influence on a new design, and even on the design process itself. For this reason, it is very important for the design team to identify all the applicable design standards at the beginning of the design effort. Failure to do this can result in major problems downstream, including delays, wasted design effort and added expense.

5.1.8 Design Constraints

Every ship design must satisfy a purpose and this is usually defined in the *Shipowner's Requirements.* While the shipowner's requirements are not really constraints they set the boundaries for the design.

Constraints apply to every ship design, both the process and the product. Time and cost are nearly always constraints, applied to both the design itself and the delivered product: the ship. Other examples of design process constraints might be the unavailability of sufficient skilled design personnel or required computer software, hardware, or network capability.

Physical constraints might be applied to the design itself for anyone of three reasons: the need to build the ship in a specific shipyard and then get it to sea, the need to maintain the ship during its service life, and the need for the ship to visit specific ports.

Assigned Weight	Attribute
1	Cargo carrying capacity
1	Acquisition Cost
2	Energy conservation
2	Manning reduction
2	Reliability
3	Minimum risk
3	Standardization

1 = 10 points
2 = 5 points
3 = 2.5 points

Figure 5.3 Example of Ship Design Philosophy

Frequently, drydock, pier, harbor or canal limitations create constraints. Hull dimensions and air and water drafts are affected most frequently. Bridge or overhead cable heights may limit air draft, the height of the uppermost point on the ship above the water surface. Harbor or canal channel depths often establish the limit on water draft, more properly the navigational draft, or this limit may be set by the sill height in drydocks to be used to maintain the new ship. Hull length and/or beam might be limited by canal lock, drydock, or building way dimensions. The available length at piers the ship will moor to might also limit hull length. These are just some examples of operational considerations that can impose physical constraints on a new ship design.

5.1.9 Design Philosophy

A design philosophy is a weighted list of desired design/ship attributes that is used in the evaluation of design alternatives. Examples of such attributes include:

- first cost,
- operating cost,
- mannmg,
- producibility,
- operability,
- maintainability,
- reliability,
- mission capability,
- sustainability,
- supportability, and
- risk (cost, schedule and technical).

Each attribute should be measurable in clearly defined units; the shipowner should agree to them all. The design philosophy is a guide used by the members of the design team as they perform trade-offs and evaluate design alternatives during design development. The need for a design philosophy increases when the number of design participants is large and/or when the design team is physically (geographically) separated. A risk in large design teams is that individual members of the team might apply their own personal priorities as they evaluate design alternatives and make decisions. The design philosophy is an attempt to keep all team members *marching to the same drummer* as they make design decisions. Figure 5.3 is an example of a design philosophy that might be used during a new ship design.

In practice, the design philosophy is tailored to suit the specifics of each trade-off study to which it is applied. Not all elements of the philosophy apply to each trade-off decision and many trade-offs will require unique performance measures to be evaluated.

5.1.10 Degree of Uniqueness

New designs cover the gamut in terms of their uniqueness. Some new designs are very similar to existing ships with modest changes, for example, somewhat more or less propulsion power or payload. Other designs reflect significant changes from current practice in specific respects, the propulsion plant type might be an example, but in all other respects they are not unique. At the extreme, and quite rare, is the design that is very different from anything considered before. The rare unique design is not only an exciting challenge for the naval architect but it affects the approach to early stage design as well.

For designs that are well understood, that is, similar to what has been done in the past, the design team will have access to a multitude of data for similar ships. This data can be used in early stage design to make quick and reasonably accurate estimates of the principal characteristics (Chapter 11 - Parametric Design) and costs of alternative concepts for the new design. This may be done using ship synthesis models, discussed in Chapter 14, that contain estimating relationships derived from parametric analyses of the body of data on existing ships. The parent ship approach may also be used if the database contains one or more ships that are sufficiently similar to the desired new design. In any case, the large body of existing data pertinent to well understood designs simplifies early stage estimating and makes it possible to readily examine the effects on performance and cost of a large number of primary design parameters, for example, speed, endurance, pay load, etc.

On the other hand, for the unique design, the database on existing ships is of little or no value. The naval architect must fall back to reliance on first principles to laboriously develop a small set of point designs, that is, conceptual designs that cover the ranges of the primary design variables of interest. More technical experts will have to be brought in to develop these point designs and they will generally have to develop more design detail than is typical in the initial design phase. An example would be the development of a point design for a high-speed multi-hull with a unique hull form. The estimate of required propulsion power is critical to sizing the hull and estimating its cost. Power at the required top speed is, in turn, a function of the full load displacement. Lacking weight data on similar designs, in order to get a reasonable weight estimate, a considerable effort might have to be expended on an initial structural design. This, in turn, might require a major effort to assess the anticipated hydrodynamic loads on the structure. The point designs, once they have been developed, can be used as parents to explore the effects of parametric variations in other, second order parameters. For the unique design, early stage design progress is slower, more difficult, and the design results are much less certain, that is, there is a higher degree of risk in the results of early stage studies of unique designs. This uncertainty can be partially compensated fot by the use oflarger design margins as discussed in Section 5.7.

5.2 DESIGN PHASES

The design process is subdivided into phases. One reason for this is that the nature of the work done, the design skills required, the number of persons participating in the design effort, the level of detail of the design deliverables and other features of the design process change over time as a design is developed. Design management is facilitated if the effort is divided into phases separated by intervals, which permit design reviews to occur, along with planning and preparation for the next design phase. Another reason for phasing a design effort is the major milestones in the typical ship development process. An example of such a milestone would be the point at which the budget for the new ship must be established. Another typical milestone would be the point at which specifications and drawings must be completed to solicit shipyard bids for the detail design and construction effort. Note that this milestone might not apply in every case; for example, if a ship design were being developed on speculation by a shipyard.

The number of design phases and the names applied to them vary and this is a source of confusion. For this discussion, the approach developed in the early 1980s as part of the IHI Technology Transfer, and defined in references 1 and 2, which divided the design and engineering effort into Basic Design and Product Engineering, is used.

Basic Design is further subdivided into four phases, designated as follows:

1. concept design,
2. preliminary design,
3. contract design, and
4. functional design.

The latter two phases are often referred to collectively as the "System Design Phase."

Product Engineering is subdivided into two phases:

1. transition design, and
2. workstation/zone information preparation.

During Basic Design, the ship is designed in its entirety, on a system-by-system basis. During Product Engineering, the ship design is translated into a form suitable for modern production techniques and necessary additional information is developed. Some experts consider Functional Design to be part of Product Engineering but it has been in-

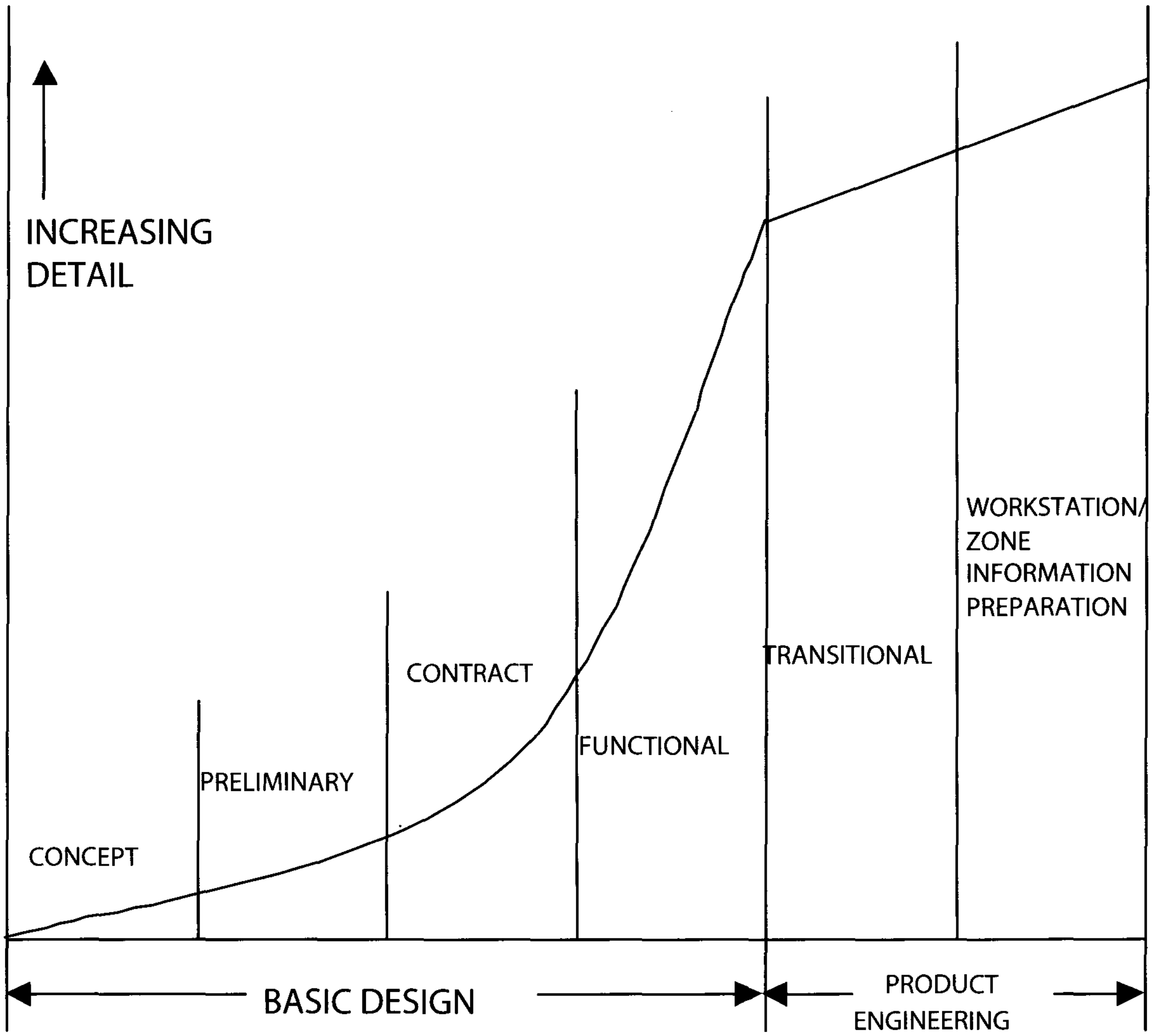

Figure 5.4 Ship Design Phases

cluded here in Basic Design since it remains systems oriented. The first three phases of Basic Design must be completed before the award of a contract for detail design and construction. Note that the traditional detail design phase has been divided here into three phases, namely, functional design, transition design, and workstation/zone information preparation.

Modem techniques for modular ship construction permit extensive pre-outfitting and pre-testing of ship blocks prior to ship assembly. This improves efficiency and saves cost by reducing on-way or in-dock time during ship assembly and by maximizing the amount of advance work done in better working conditions at vendors' facilities or in enclosed buildings at the shipyard. Use of these techniques increases the time required for detail design as well as the level of detail and completeness of the detail design package, which is now up to 20 to 30% larger than in the past. Another effect has been to largely eliminate the traditional overlap between detail design and ship construction. The current philosophy is to resolve problems in the detail desIgn package before *cutting steel.* The extra time and effort spent on detail design is more than recovered by a more efficient construction effort, as can be seen by very flat learning curves for multiple ship construction in Japanese shipyards. That is the benefits of learning are obtained because mistakes and rework on the first ship are eliminated by better and completed design.

Figure 5.4 depicts the design phases and the increase in detail as a design progresses.

5.2.1 Concept Design

This first design phase, referred to herein as *Concept Design* (CD), is sometimes referred to in the naval ship world as the Cost and Feasibility Study phase, or simply the Feasibility Study phase. The principal objective of this phase is to clarify the shipowner's requirements, that is, the ship's mission and principal required performance attributes, which reflect the desired balance between capability and affordability. (See Chapter 7 - Requirements Definition.)

Another objective is to develop a concept design, which satisfies the requirements, as well as a cost estimate and a risk assessment. From the designer's point of view, the objective during this phase is to work with the shipowner to understand and define the ship's mission, that is, to help the shipowner decide what it is that he needs and can afford. When this has been done, a concept design is developed which reflects this mutual understanding.

At the outset, the shipowner will know that he has a need for a new, converted or modified ship and will know in general what functions the ship must perform. However, the shipowner often will not know specifically what the performance requirements are for speed, fuel endurance, cargo capacity, etc. If the shipowner does have some specific values in mind for these variables, the shipowner may not know whether they are compatible with the budget. Thus a systems analysis is required which couples mission analysis with economic analysis. Ranges of each of the key ship parameters are explored in a systematic way; ship feasibility studies are developed for attractive combinations of the parameters, the cost and performance of each total-ship alternative is estimated, a cost-benefit analysis is performed, and feedback is obtained from the shipowner as to his preferences.

Typically several cycles of synthesis and analysis are performed, punctuated by interactions with the shipowner, during which the range of options studied is progressively narrowed. Through this process, a consistent set of performance requirements is established, which can be satisfied by a practical ship design solution and is within the shipowner's budget.

The role of the design team is to perform parametric studies that sketch out the design alternatives of interest in sufficient detail that the cost (capital and operating), performance, and risks (cost, technical and schedule) of each can be assessed and compared. The alternatives are often referred to as feasibility studies because the feasibility of each postulated combination of the major design requirements must be established, that is, is there a viable design solution for each case? Where there isn't, that combination of requirements can be rejected. Where there is a viable solution, that solution can be input into the cost-benefit analysis.

Because performance, cost and risk are being compared among the alternatives, *relative* accuracy and consistency among the alternatives is stressed rather than *absolute* accuracy. Collectively, the set of alternatives must illuminate the capability versus cost versus risk trade-offs of interest to the shipowner. At the conclusion of this process, the mission of the new ship will have been defined along with the principal ship performance requirements, that is, required ship capabilities. In addition, a feasibility study will have been created which represents an initial solution to the stated requirements. Normally, near the end of the phase, this feasibility study is developed in greater detail to become a concept design. This is done to reduce risk, improve the cost estimate, refine and validate the most important derived ship performance requirements, and establish a baseline for the start of preliminary design and its major trade-off studies. The products of a typical naval single feasibility study and a concept design are listed in Tables 5.1 and 5.11,respectively.

Figure 5.5, based on a figure in reference 4, classifies all seagoing ships in two broad categories: transport and non-transport, with three and four sub-categories, respectively. The above process description generally applies to all ofthe sub-categories.

TABLE 5.1 Feasibility Study Products (U.S. Naval and Government Ships)

Feasibility Study Report, documenting the following:

Essential performance requirements

Principal hull dimensions and hull form coefficients (Cp, Cx)

Area/volume summary

Configuration sketches: inboard profile and main deck plan

Payload definition, for example, space, weight, critical dimensions, adjacencies, required support services

Description of mission-critical systems and features

Weight/KG estimate, I-digit level

Propulsion plant type, installed power, and number of propulsors

Installed electric generating capacity

List of major equipment

Manning estimate

Speed/power estimate

Endurance fuel estimate

Intact stability check

Estimates of critical performance aspects, as required, e.g., radiated noise or seakeeping

Cost estimate

Technical risk assessment and risk management plan

In the case of ships designed to transport bulk or general cargo from point to point as elements of a larger transportation system, analyses of the overall system, including its land-based elements, are typically performed. For the ship portion of the system, the fundamental decisions to be made are: number of ships, payload (carrying capacity, in both weight and cubic terms), and speed. Computer models are applied to simulate the operation of a single ship or an entire fleet. Such models range in complexity from simple deterministic models to complex time domain simulations. They generally incorporate simplified design models with the ability to quickly generate ship characteristics corresponding to various combinations of payload and speed. The models estimate the capital and operating costs for each alternative. Optimization techniques can be applied to the major variables to compare alternatives and search for the optimum or graphical output of performance metrics can be shown for the study *option space* so that a human decision-making selection can be made.

It is more difficult to apply the classical systems analysis techniques to ships in the non-transport categories. For the latter types, the number of critical mission characteristics is generally greater and the ability to analyze and compare mission performance as related to these characteristics is more difficult. For example, it is more difficult to predict the ability to detect and catch fish than it is to predict the speed of a transport ship. In a multi-mission warship, arriv-

TABLE 5.11 Concept Design Products (U.S. Naval and Government Ships I

Concept Design Report, documenting the following:
Performance specification (initial draft)
Body plan and appendage sketch
Area/volume summary
Concept general arrangement drawings (space *blocks* allocated by function)
Topside arrangement sketch
Payload definition
Description of mission-critical systems and features
Weight estimate
Concept midship section
Propulsion plant description
Machinery arrangement sketch
Electric load analysis and generated selection
Simplified one line diagrams
Master Equipment List (MEL)
Speed-power curve
Manning estimate
Endurance fuel analysis
Estimates of critical performance aspects, as required
Cost estimate
Technical risk assessment and risk management plan

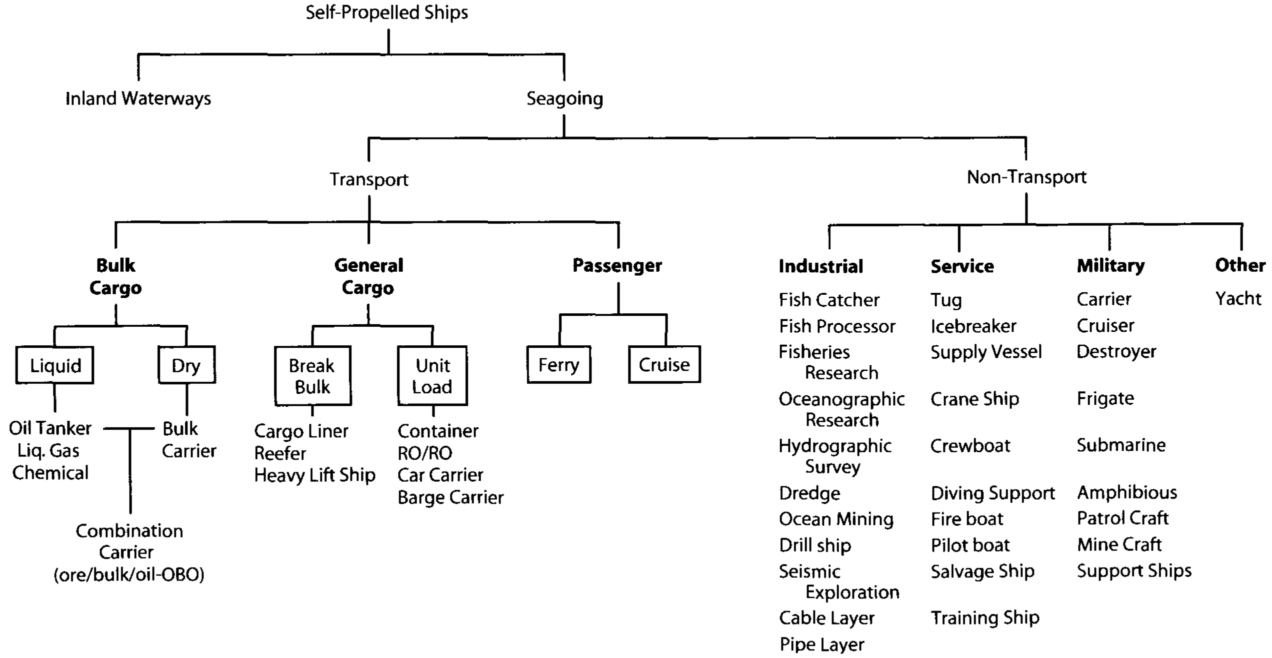

Figure 5.5 Ship Type Categories

ing at a single figure of merit is challenging since it is generally scenario dependent.

5.2.2 Preliminary Design

Design work, for the specific ship, begins in earnest in the preliminary design phase and the size of the design team and the cost of the design effort take a big jump. The following are the objectives of this phase:

- validate the top level ship performance requirements and develop second tier requirements,
- establish ship size and overall configuration,
- select major ship systems,
- quantify ship performance,
- reduce or eliminate major technical, cost and schedule risks,
- refine capital and operating cost estimate, and
- develop draft version of the Build Strategy (see Chapter 14 - Design/Production Integration).

Since the eventual cost and performance of the new ship will be established largely by the end of the preliminary design phase, the work done during this phase is very important. A feasibility study or concept design that satisfies the performance requirements developed in the previous phase will be available and this forms the starting point for the preliminary design effort. During this phase, formal trade-off studies are performed on design issues that will have a major effect on ship size, overall configuration, performance, cost or risk. The study of issues that do not have a major impact on these parameters should be deferred to the following phase. Failure to do so can waste resources and divert the attention of the design team.

Some examples of pertinent issues for trade-off study in this phase are:

- hull proportions (LIB, *BID*, etc.),
- hull shape (transom vs. cruiser stem, bow bulb vs. no bulb, topside flare vs. tumblehome, etc.),
- general arrangement,
- propulsion plant type (low speed diesel, medium speed diesel, gas turbine, integrated electric, etc.), (Often addressed in Concept Design phase),
- deckhouse size and location,
- mission-critical payload features, (hardware components, space allocation, arrangement, etc.),
- hull structural configuration, and
- crew SIze.

The ship impacts of some issues studied in this phase will be so large that whole ships must be *wrapped around* the candidates being studied in order to get valid assessments of total ship impacts. These whole ship alternatives may be developed at the feasibility study level of detail or may require greater detail. An initial design baseline is establis~ed early in the design phase to serve as a point of reference for the trade-off studies. This initial baseline is generally the concept design created at the end of the previous design phase. Usually the design baseline is updated several times before the end of the preliminary design phase so that the results of major trade-off studies can be incorporated as they are completed.

The preliminary design is developed beyond the initial concept design in all technical areas, regardless of whether they are subject to formal trade-off studies. In design areas not subject to the investigation of design alternatives, a reasonable baseline concept is selected and defined to the appropriate level of detail. For many ship systems, this is the identification and approximate sizing of major system components and the development of a simple one-line diagram of the system. System alternatives will be studied in the following phase.

The Build Strategy for the ship (5,6), reflecting zone construction, is drafted during this design phase, if not earlier. Production considerations are reflected in the design work to the extent practical. For example, in the development of the hull form and superstructure configurations and in defining the locations of decks and bulkheads within the ship, maximum use is made of flat plates and readily formed shapes. If a shipbuilder is developing the design, the shipyard production specification (Shipbuilding Policy), which defines the design processes and production methods and processes to be used to build the ship, must be developed during this phase, if it does not already exist. This specification will influence the contract design effort and the parallel completion of the build strategy. If the design team does not know which shipyard will build the ship (as in the case of a build competition), the Build Strategy may have to be *generic*, that is, suitable for all potential shipbuilders.

Major emphasis is placed on predicting performance to validate that the stated performance requirements have been satisfied. These predictions might include ship speed, seakeeping, station keeping, ability to traverse along a defined track line, acoustic performance, cargo on-toff-load rates, or the ability to perform critical missions in a seaway, as typical examples. If the hull form is unusual and hydrodynamic performance is of critical importance, limited model testing may be done to validate performance estimates. More often, model testing is deferred to the following phase.

Risk identification and reduction is another area of emphasis. Major risks must be identified and alternative ways to reduce them explored. These generally include fallback design options with lower risk but less performance. The objective is to reduce the risks associated with the completed preliminary design to *low* or, where this is not possible, to develop a clear and detailed plan to accomplish this by the end of the next design phase. This must be accomplished before the next design phase is entered. The products of a typical preliminary design are listed in Table 5.III.

Note that the preceding discussion has assumed that a new ship is being designed. Frequently, ship conversions or modernizations are also evaluated as possible solutions to the shipowner's requirements during this design phase.

5.2.3 Contract Design

The principal objectives of the contract design phase are:

- confirm ship capability and cost to the prospective shipowner,
- provide a meaningful and accurate bid package for shipbuilders, and
- provide criteria for shipowner acceptance of the ship.

Extensive additional engineering effort is required to achieve the first objective. Emphasis is placed on the development and refinement of ship systems across the board. Trade-off studies deferred from the previous phase due to their lesser ship impacts are now performed. The technical portion of the bid package is developed by the design team and consists of a ship specification, drawings, and other ship descriptive data, for example, the weight estimate.

For each ship system, the following tasks must be performed:

- derive lower tier performance requirements from the higher level ship performance requirements,
- develop and evaluate alternative system concepts (where this has not been done in the previous phase),
- make system selections,
- complete engineering work on the selected system, and, finally,
- develop system specifications and drawings.

The ship hull form, including appendage definition, and general arrangement are further refined. Formal configuration control is often invoked near the mid-point of this design phase. Arrangement drawings are developed for many of the ship's internal spaces and for topside system installations, for example, anchoring and mooring, boat handling, communications and navigation, and helicopter facilities.

As the ship systems are designed, careful attention is paid to the integration of the ship systems and their human operators and maintainers. As part of this effort, for naval ships, the ship manning requirements are refined and training requirements are defined. Reliability, maintainability, and availability (RMA) analyses are performed, as are studies and design work related to the ship's maintenance and

TABLE 5.III Preliminary Design Products (U.S. Naval and Government Ships)

Preliminary Design Report, documenting the following:
Performance specification
Lines drawing and appendage sketch
Area/volume report (req'd vs. actual)
General arrangement drawings (to individual compartment level)
Topside arrangement drawing
Line of sight analysis
Payload definition
Descriptions of principal ship systems and features
Weight report (3-digit level, KG and LCG)
Structural midship section
Preliminary scantling drawings
Propulsion system analysis
Machinery arrangement drawings
Shafting arrangement
Preliminary propulsor design
Electric load analysis
HVAC load analysis
One line diagrams
Typical space arrangements
Deck systems arrangements
Ship control and communications systems analysis
Preliminary Master Equipment List (MEL)
Preliminary ship manning analysis
Stability analysis, intact and damaged
Speed-power curves
Endurance fuel analysis
Seakeeping and maneuvering analyses
Model test plan
Other performance estimates, as required, for example, radiated noise
Preliminary availability analysis (Ao)
Maintenance concept
Supportability concept
T&E plan (draft)
Preliminary safety analysis
Build strategy (draft)
Shipyard production specification (Shipbuilding Policy)
Cost estimate
Technical risk assessment and risk management plan

support requirements, often referred to as Integrated Logistics Support or ILS.

The ILS effort addresses issues such as:

- the ship maintenance philosophy (for example, what maintenance work will be done at sea by the ship's crew vs. work done in port by shore-based personnel),
- the repair parts required to be stowed aboard ship,
- parts commonality and interchangeability between ships,
- re-supply of the ship with stores and repair parts,
- approach to ship configuration control and the tracking of maintenance actions,
- the required shore-based facilities for ship support including spare parts stowage and maintenance facilities, and
- planned maintenance strategy and schedule (restricted availabilities, overhauls, and dry dockings).

The Build Strategy drafted during preliminary design is validated and approved during this phase (5). It includes the design and engineering plan, and the block and zone definitions to be employed during ship construction. The ship production plan is also developed. It includes the key event schedule and the selected approaches to advanced outfitting and ship assembly and construction.

Technical specifications required for the advanced ordering of long lead equipment and materials are developed. All aspects of ship performance are analyzed and the stated performance requirements validated. A full program of hydrodynamic model tests is typically performed for naval ships, some of which support the propeller design, which is also typically developed in this phase. Final tests of the design propeller mounted on the final hull model may not be completed until the following phase, however.

Traditionally, critical ship systems and spaces such as the anchor handling system and the navigation bridge were modeled using small or full-scale physical mockups to ensure correctness and to permit review by the shipowner. Today, however, 3-D models with simulation and walk-through capabilities, developed by computer, are replacing physical mockups. Ifland-based testing will be required for essential elements ofthe ship, these tests and the associated site requirements will be defined during the subsequent functional design phase.

The ship specification is perhaps the most important product of contract design (see Chapter 9 - Contracts and Specifications). The specification is, of course, essential if the shipowner plans to have shipbuilders bid for the detail design and construction task. However, even if a shipbuilder is developing the design, the specification is required in order to acquaint others in the yard with the work required and to arrive at a valid estimate of the anticipated build cost. The ship specification typically is a mix of performance and *how to* specifications, the latter reflecting the shipowner's preferences and the shipbuilder's preferences if the specification is prepared by the shipbuilder. It includes thtHest and trials requirements for the new ship, as well as acceptance criteria for each test and trial requirement. These criteria must be met for the shipowner to accept the ship.-The ship specification also contains requirements for the documentation that must be delivered with the ship, documentation necessary to properly support the ship throughout its life. Because of the importance of the ship specification and the drawings referenced in it, it is carefully reviewed prior to the completion of the design phase. In the review process, specifications and drawing integration is emphasized, to ensure that there are no conflicting requirements between sections of the specification and/or the various drawings. Obviously, the specification language must be unambiguous. Table 5.IV lists products that may be included in a contract design.

5.2.4 Functional Design

This design phase, and the other two that follow, are only briefly described herein. See references I, 2, and 7 for additonal detail and other references.

During Functional Design, the Contract Design is developed further to complete the design on a system-oriented basis. The products of a typical functional design are listed in Table 5.Y. All design calculations and configuration definition are completed and all design decisions still outstanding are made.

Detailed naval architectural calculations are performed, including structural and vibrations analyses. The sizing of all structural scantlings is completed. All hull outfit is defined in detail, including the complete definition of all material. All marine engineering and electrical design calculations are completed, as are system arrangement drawings and diagrams.

System arrangements (drawings or computer models) are prepared for systems such as the mooring system that do not lend themselves to diagrams. Sized distributive systems are shown on the system plans. The completed diagrams for piping, electrical and HVAC show pipe, cable and vent duct sizes, cable types, bills of material and system routing in assigned wire ways or system corridors.

Typical sections are indicated for pipe and vent duct runs. The first revision of the budget control list is issued, which advises all concerned of updated material quantities and weights. Manufacturing drawings are prepared for all long-lead-time items that are to be built by the shipyard. Purchase technical specifications not developed earlier are completed. Shipowner and regulatory body comments on and approvals of the completed design are obtained. Vendor se-

TABLE 5.1V Contract Design Products (U.S. Naval and Government Shipsl

Ship specification	HVAC load analysis and design criteria	Hydrodynamic model test results, for example, resistance, propeller open water, self-propulsion, maneuvering, seakeeping, etc. and performance assessment reports
Lines drawing	Ventilation and air conditioning systems diagrams	Stack gas flow analysis
Appendage drawing	Piping systems analysis	Evaluations of other aspects of required performance
General arrangements (outboard profile, inboard profile, all decks and holds)	Diagrammatic arrangements of all piping systems	Availability analysis (Ao)
Topside arrangement	Fire control diagram by decks and profile	Maintenance Plan
Capacity plan	Mechanical systems arrangements, for example, deck, hull and ship control systems	Supportability Plan
Weight report (3-digit level, KG and LCG, 20-station weight distribution, gyradii)	Living space arrangements (berthing, messing, sanitary, recreation, etc.)	Crew Training Plan
Structural design criteria manual	Commissary space arrangements	T&E Plan
Midship Section	Pilot House, Chart Room, and other working space arrangements	Safety analysis
Steel scantling drawings (decks, bulkheads, shell expansion, typical sections, deckhouse)	Interior communications system diagram	Procurement specifications for long-Iead-time and other important outfit components, for example, main propulsion engines, diesel generators, reduction gears, anchor windlass
Machinery control system diagrams	Master Equipment List (MEL)	Models and Mockups
Propulsion and auxiliary machinery arrangement drawings (plan views, elevations, and sections)	Preliminary ship manning document	Cost estimate
Propulsion shafting arrangement	Pollution control systems report	Technical risk assessment and risk management plan
Propeller design	Loading conditions	Initial regulatory body review
Electric load analysis	Floodable length curves	Building plan
Electric power and lighting systems - One line diagrams	Trim and stability booklet	Budget control list (estimated weight of all required material by material family or cost code)
Fault current analysis	Damage stability analysis	Production plan
Navigation system diagram	Endurance fuel analysis	

lection is completed and vendor drawings are approved. Advance equipment and material is ordered.

5.2.5 Transition Design

During transition design, all design information is transitioned from systems to block and zone orientation as complete block and zone design arrangements and the ordering and assigning of all materials are completed (7). Drawings and product models also indicate subdivisions and material-ordering zones. The Shipyard's Shipbuilding Policy and the Contract Build Strategy will define how the ship will be built; for example, how major machinery items will be loaded, how auxiliary machinery and other components will be fitted, what work will be done on-unit, on-block (before and after turnover), and on-board. The breakdown of each zone into sub-zones is also defined.

A virtual prototype of the ship is developed, either on paper or by 3-D modeling in the computer. Zone design composite arrangements are developed from the distribution system routing diagrams developed in the previous phase. The zone design arrangements show all visible items seen from the viewing plane, no matter how small. All elements are included. The required zone/unit material quantity is also developed. Interference checking occurs as the work proceeds. All working, maintenance, and access requirements are checked.

Structural design work is completed and structural drawings for each block are developed, each with an accompanying bill of material.

5.2.6 WorkstationlZone Information Preparation

During this phase, all drawings, data and other information required by the production and other service departments to construct the ship are prepared. This includes drawings,

TABLE 5.V Functional Design Products

Hull	Rudder and propeller lifting gear arrangement	Electrical
General arrangement- Compartment and access (C&A) drawings	Anchor handling arrangement	Electrical Load analysis
Outboard profile	Mooring arrangement	One-line diagram
Lines drawing	Life-saving equipment arrangement	Short circuit analysis
N.A. drawings, for example, hydrostatics, cross curves of stability, docking drawing	Hull piping system diagrammatics	List of motors and controllers
Block arrangement and list	Purchase Technical Specifications (PTS)	List of feeders and mains
Frame body plan (based on faired lines)	Advanced Material Ordering (AMO) Lists	Electrical equipment and installation diagrams
Structural block drawings with scantlings	Steel List per block	Switchboard drawings
Major foundation drawings		List of Portable electrical equipment
Welding plan	**Machinery and Piping**	Electrical system weights
Hull fitting drawings	Machinery arrangement	Purchase Technical Specifications (PTS)
Hull weights, centers, and block lifting data	Shafting arrangement	Advanced Material Ordering (AMO) Lists
Lists of hull outfit	Stern tube arrangement	
Lists of hull fittings	Machinery space and wheelhouse control console arrangement	**HVAC**
Nameplates and Notices	Machinery piping system diagrammatics	Heating and cooling analysis
Summary paint schedule	Diesel exhaust arrangement	HVAC diagram and equipment list
Summary deck covering schedule	Lifting gear in machinery space	HVAC insulation schedule
Summary hull insulation schedule	Machinery and pipe insulation schedule	HVAC system weights
Furniture list	Unit and equipment foundations	Purchase Technical Specifications (PTS)
Plumbing and fixture list	Machinery and foundation weights	Advanced Material Ordering (AMO) Lists
Galley arrangement	Purchase technical specifications (PTS)	
Accommodation arrangement	Advanced material ordering (AMO) Lists	**Production Planning**
Steering gear arrangement		Work station information plan and schedule
Rudder and rudder stock arrangement		Block outfitting and erection schedule
		Zone outfitting schedule
		Tests and Trials schedule

sketches, parts lists, process instructions, and production aids such as templates, marking tapes, and software to control robots doing plate burning/marking and pipe fabrication. The work required to produce an entire zone is broken down into many work packages, each defining a much smaller task. A typical guide for work package size is that no more than three workers can complete the work defined by the package in no more than two weeks, or no more than 200 work hours.

Production planners size the work packages and either use the information needed by the workers, prepared by Engineering and develop it further to complete the package. Only the information needed to complete each work package, including production aids, is included. Each work package is broken down into separate workstations. Again, the workstation information is complete, the worker needs no other information to complete the job, and no unnecessary information is provided. The workstation information is provided on A4 or letter size sheets and typically consists of sketches and a parts list. The sketches show the work as the worker will see it; upside down, for example, if the work is to be done upside down. Structural workstation/zone information is developed for: burning plate, cutting shapes, processing plates or shapes (bending, flanging, or drilling), subassembly construction, assembly construction, block construction, and block erection. Block assembly sketches are developed; these permit the designer to consider block access requirements during construction. Planning and production personnel also jointly develop work sequence sketches. They define in considerable detail how the ship will be put together. Outfit work station/zone information is developed for shops, assemblies, blocks and zones. For the shops, workstation information for both processing and assembly is developed for hull fittings, pipe, sheet metal, foundation structure, joiner, paint, and electrical. Workstation information also is developed for machinery installations on units.

5.3 DESIGN PROCEDURE

In the preceding section, the design process was described in terms of the design phases that a design normally passes through as it evolves. In this section, the nature of the work done in the early design phases is described in more detail. Again the focus is on naval design.

The early design phases are the most mysterious to, and most misunderstood by, those who do not practice the art of ship design. A generic step-by-step procedure is outlined for developing a single ship feasibility study, the first step in the design process, and a single conceptual design. Then, broader aspects of the subsequent design development process are described. Emphasis is given to the trade-off study process, the concept of design baselines and their updates, and the design integration process. The reader is reminded that normally many ship feasibility studies are developed in the process of assisting the shipowner to decide on the major requirements for a new ship. Several conceptual designs may also be developed as major design alternatives are explored.

5.3.1 Getting Started

Once the major performance requirements and constraints for a new design have been established, design work can begin. Initial attention is focused on the mission(s) of the ship and its payload (weapon suite) or cargo requirements. These two parameters will have a dominant effect on the size, configuration and key features of the completed design, as well as on the process used to arrive at the design. To illustrate, consider the design of an aircraft carrier, a containership, a buoy tender, and an inter-island passenger/cargo ship that must beach itself at ports of call without normal pier facilities.

The primary payload of the aircraft carrier is its air wing. The primary mission of the carrier is to support the air wing: to house, maintain, fuel, arm, launch and recover, and provide command and control functions for the aircraft in the air wing and to care for the pilots and other air wing personnel. Because of the dominant effect of the carrier's flight deck and hangar on its design, initial design effort will focus on the flight deck and hangar and their configuration.

In the case of the containership, the number of containers to be carried is critical. Initial design effort will focus on the arrangement of these containers. How many will be stowed in the hull and how many above the weather deck? Based on the container dimensions, what are appropriate hold lengths and what are sensible hull beam and depth possibilities based on the number of container rows and levels to be stowed in the hull?

In the case of the buoy tender, buoy handling will be addressed first. Will buoys be handled forward or aft of the deckhouse? How will the buoys and their anchors and chains be lifted on and off the vessel?

In the case of the inter-island passenger/cargo ship, the required beaching capability is addressed first. What beach slopes are anticipated and how much cargo weight can be brought how close to the shore line for various combinations of hull dimensions and fullness coefficients? Once the ship is beached, how will passengers and cargo be moved from the ship to the shore?

These examples demonstrate that the design approach is influenced by the ship's mission and payload or cargo characteristics, as well as by the attributes of the ship itself. The ship designer will initially focus on gaining a full understanding of these requirements and characteristics and formulating, in their mind, overall ship concepts and configurations that will satisfy them. In doing this, the required ship design speed will be a primary consideration. Many concepts suitable for relatively low speeds will not be feasible if the required speed is high.

The naval architect will also judge whether the design will be weight, volume, or *main deck* limited. In a weight-limited design, the buoyancy required to float the weight of the ship and its payload establishes the ship's principal dimensions. In a volume-limited design, the internal space required to accommodate the payload and other ship functions establishes the principal dimensions; thus space analysis is of major importance from the outset. For weight-limited designs, space requirements need not be rigorously addressed in the initial design cycles. In a main deck limited design, the objects to be carried or built upon the deck establish the ship's length and/or beam. The aircraft carrier is an obvious example. The lengths of most surface combatant ships are determined by the so-called *stack-up* length, the sum of the deck lengths required for weapons, sensors, propulsion air intakes and exhausts, aviation facilities, anchor handling and mooring equipment, etc. (see Chapter 54 - Naval Vessels). Today most ship types are volume-limited.

5.3.2 Feasibility Study

The development of a ship feasibility study is the first step in the design development process for naval ships and is often performed by shipowners for complex commercial ships. Four primary physical criteria must be satisfied by any ship design, in addition to the requirement that the design elements must be packaged in a feasible overall ship configuration. These physical criteria are, available internal volume must equal or exceed the total required volume, weight must equal buoyancy, there must be satisfactory intact stability, and the installed propulsion power must be capable of propelling the ship at the required top speed.

These four criteria must be addressed in the initial design process. A typical sequence of steps followed in developing a feasibility study is shown in Figure 5.6. The four primary criteria are noted down the left side of the figure. The steps in the generic design process are numbered in the figure and are discussed below.

It is important to note that the sequence of steps depicted in the figure is not inviolate. A different sequence is often better suited to a particular design problem. Also, there is an interaction between the analytical process described below and the process used to define the external configuration of the ship. Some designs lend themselves to. the very early definition of some features of the external configuration. When this is the case, it can affect the steps in the analytical solution procedure. Regardless of the sequence used, the same solution should be arrived at, if consistent assumptions and decisions are made as the iterative process unfolds. Each step will be described in the following sub-sections.

5.3.2.1 Principal performance requirements

At the outset, three principal performance requirements must be known or assumed. They are, payload (cargo deadweight and stowage factor), maximum or sustained speed (design speed), and fuel endurance (design voyage distance).

Values for these can be found in the different ship type design chapters in Volume II of this book. In addition, assumptions must be made for certain ship characteristics, including the ship type, hull type, propulsion plant type, principal hull form coefficients, and the design margins to be applied. The effects of varying the latter assumptions can, and often are, explored by performing additional feasibility studies.

By *ship type* is meant the overall hull configuration and method of support, for example, conventional displacement monohull, SWATH, planing monohull, catamaran, trimaran, hydrofoil, air cushion vehicle (ACV), or surface effect ship (SES). As the term *hull type* is used here, it refers to major features of the hull form: transom vs. cruiser stem, flared vs. tumblehome topsides, bulbous bow vs. no bulb, etc. Note

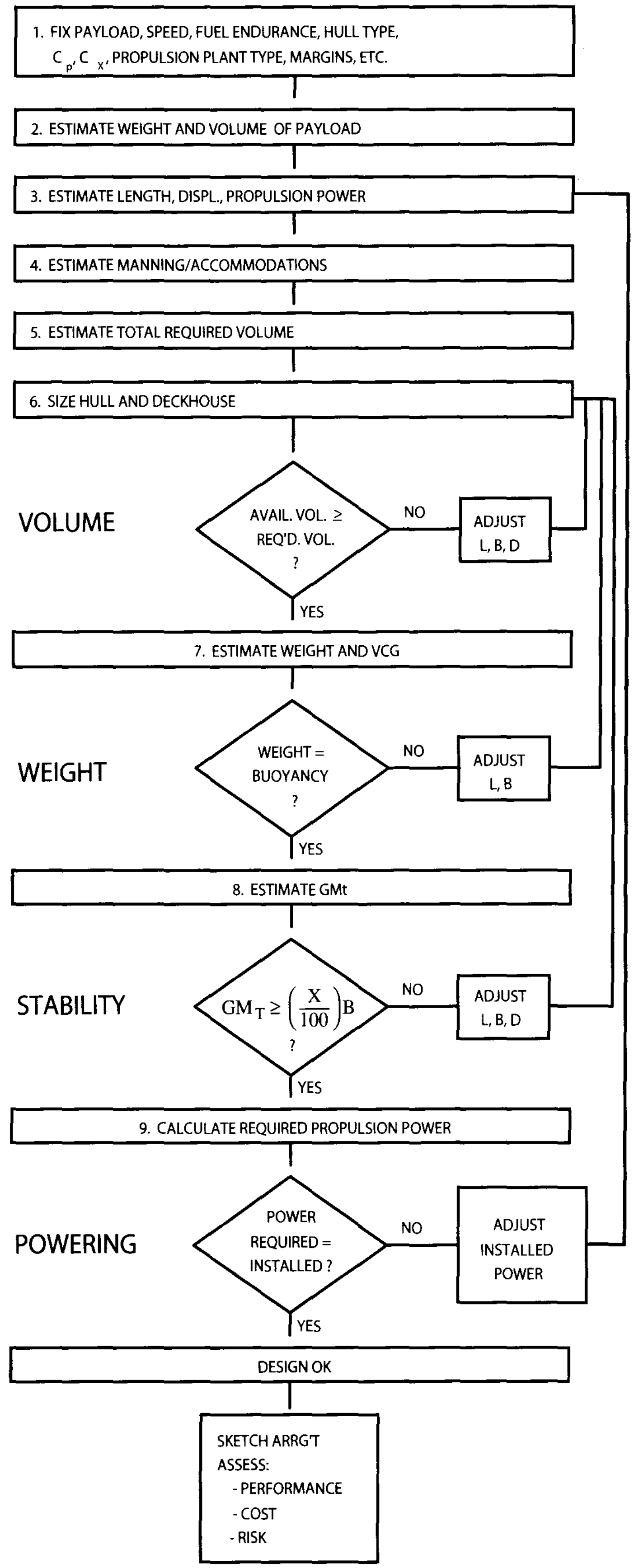

Figure 5.6 Feasibility Study Process

that the procedure outlined herein applies in principle to any ship type. The specific steps followed will vary, especially for the non-displacement ship types.

The propulsion plant type might be medium speed geared diesel, low speed directly connected diesel, geared gas turbine, or geared fossil fuel or nuclear steam turbine, all connected by shafts to propellers in the conventional manner. Electric drive or integrated electric drive plants might be considered, with a variety of generator prime movers. Combined plants such as Combined Diesel or Gas Turbine (CODOG) might be considered as well as various propulsors, including conventional open propellers, water jets and podded propulsors. To develop a single feasibility study, a single plant type must be assumed. Other propulsion plant alternatives are often evaluated with the aid of additional feasibility studies.

For a displacement monohull, the principal hull form coefficients are the longitudinal prismatic coefficient, Cp, and the maximum section coefficient, Cx. For many commercial ships with Cx about 0.98, Cb is used instead of Cpo Together these coefficients establish the block coefficient, Cb. Cp has a major influence on hull resistance and hence powering. Cx has a major effect on the vertical center of buoyancy and on the vertical center of gravity of items stowed low in the hull. Hence it has a significant effect on intact stability. Both coefficients affect the space available in the hull as well as the buoyancy provided by the hull. Initial values of these coefficients are selected based on the designer's experience and judgment. Alternative combinations of values are often studied later.

Design and Construction (D&C) margins, also known as *acquisition margins,* are applied to early stage design estimates to account for unknowns, errors in prediction techniques and the likelihood of design changes as the design requirements are refined during design development. Construction margins are applied to compensate for growth during construction. In some acquisitions, the shipbuilder will not be known during the early design stages; nor will the many vendors who will supply equipment. These uncertainties also translate into weight and KG uncertainties that are addressed by margins. It is expected that D&C margins will be depleted as the ship design and construction process unfolds. Typical margin categories include weight, KG rise, ship service electric power, HVAC loads, hull resistance, space and accommodations. Design and Construction margins are separate and distinct from service life allowances, which some shipowners require to be provided in a new ship at delivery. The latter allowances are provided in anticipation of growth during the ship's life of attributes such as weight, KG, and required electric power. Appropriate D&C margins and service life allowances must be incorporated in the feasibility study. The ship designers are responsible for the selection ofD&C margins; they must also provide for all shipowner-specified service life allowances.

5.3.2.2 Payload weight and volume estimation

Payload weight (cargo deadweight) and volume are estimated. The definition of *payload* must be clear and consistent with the estimating relationships described later. The term *payload* as used here refers to weapons and the equipment, supplies and crew to support the cargo and/or other items directly related to the ship's mission. Ship endurance fuel, fresh water, provisions and other consumables are not included. Some might define this *payload* as consisting solely of variable load items carried to perform the ship's mission. For ship sizing purposes, however, it is probably best to take a broader view and define payload to be any built-in ship systems and spaces that directly support the ship's mission, in addition to the variable loads themselves. An example would be the scientific gear and laboratory spaces on an oceanographic research ship, as well as the equipment used to raise and lower the scientific gear overboard from the deck of the ship. In this example, the payload consists of a number of installed systems and shipboard spaces, as well as scientific supplies and equipment that can be loaded onto and off of the ship. Payload weight and volume estimation is relatively straightforward for commercial ships such as crude oil tankers, bulk carriers or container ships where the entire payload is cargo, although variable cargo densities can complicate the task. It is more difficult for payloads that include installed ship spaces and systems. Note that the payload volume, which must be provided within the hull and/or the deckhouse, must be distinguished from payload volume, which will be carried external to the hull envelope, such as containers loaded on deck.

5.3.2.3 First estimates of principal characteristics

Initial estimates are made of hull length, full load displacement and installed power. Almost any values can be used for the initial estimates but the closer they are to the final result, the fewer iterations will be required to get to closure, when using the spiral design or similar single point design approach. These estimates are generally based on empirical plots or equations derived from a statistical analysis of existing ship data for the particular hull type and ship mission being considered. Displacement might be estimated from a plot of payload weight versus displacement (or Deadweight Coefficient for commercial ships), length might be estimated from a plot of length vs. displacement, and installed power might be estimated from a plot of power per ton versus Froude number.

5.3.2.4 Determination of manning/accommodations requirements

The total number of accommodations to be provided is estimated. This is generally based on a manning estimate (provided by the shipowner for commercial ships), increased by an allowance for transients and perhaps a D&C margin and/or a service life growth allowance.

5.3.2.5 Estimation of required volume

The total required internal volume is estimated. Initially, this is a gross figure that reflects the payload (cargo) volume plus the volume required for crew living, propulsion machinery (total machinery space volume, including air intakes, exhaust uptakes, and shaft alleys), tankage, stores, access, ship control spaces, voids, and other miscellaneous spaces. For the initial estimate, an empirical plot of total internal volume versus payload (cargo) volume is often used, based on data for ships with similar missions and hull types. More detailed estimates will be made in later iterations.

5.3.2.6 Sizing of hull and deckhouse

The hull and deckhouse are sized to provide the required internal volume. A split between the hull and deckhouse volume is chosen. This might be based on a factor chosen from previous designs, or it might be based on a tentative deckhouse sketch with an associated deckhouse volume. Deducting the estimated deckhouse volume from the total required volume yields the required hull volume. Hull length, beam, depth and block or prismatic coefficient, are adjusted until the necessary hull volume is provided. Empirical plots of hull proportions such as LIB, *BID,* and LID for ships with similar hull types and missions are often used as a guide in this process. Extreme proportions will often lead to problems: too great a LIB ratio and too Iowa *BID* ratio could result in deficient stability, and too great an LID could result in adverse hull girder strength. *Large object volumes* with specific minimum dimensions to be accommodated within the hull, must be considered when selecting the principal hull dimensions. Examples might be an engine room, a large cargo hold, an aircraft hangar or a missile magazine. *Large object volumes* typically have a vertical height that exceeds one normal deck height; they may also have an unusually large length or beam.

5.3.2.7 Weight and center of gravity estimates

The full load weight and Vertical Center of Gravity (VCG) (KG) are estimated. Lightship weight groups and load items are treated separately. Lightship weight components are initially estimated in major groups, using selected *parent ships* or empirical plots of data for ships with similar missions and hull types. Hull structural weight might be estimated from a plot of hull steel weight versus LBDIlOO (cubic number), machinery weight might be based on a plot of machinery weight versus installed power for the assumed plant type, etc. Living space outfit is generally a function of crew size while hull outfit might be a function ofLBD/100. Lightship KG is generally estimated by using *KGID* factors for the individual weight groups based on data from similar ships. Load items are estimated or computed. The variable portion of the payload weight estimated in Sub-section 5.3.2.2 is known. Endurance fuel weight can be estimated initially, and then computed once a speed-power curve has been estimated in Sub-section 5.3.2.9. Load KG is estimated by assigning KG values to the individual load items based on the naval architect's vision of the ship configuration and data for similar ships.

At this point, weight is checked against buoyancy. Since L, B, Cp, and Cx are known, the draft required to float the ship's weight can be computed. If it is too great (navigational draft constraint exceeded or freeboard too low, based on either required regulatory freeboard or empirical criteria derived from successful designs), Land/or B can be increased, which affects available volume and weight. Hull depth might be reduced in an attempt to avoid excess volume, if adequate freeboard could be achieved. Deckhouse size (volume) also might be reduced. Note that Cp and/or Cx also could be increased at this point to reduce draft but the naval architect may choose not to, seeking a solution at the selected Cp and Cx values with the idea that other Cp and Cx combinations also will be studied later. If the calculated draft is too low, perhaps not enough draft to swing a propeller of reasonable diameter, Land/or B could be reduced; D and/or deckhouse size would have to be increased commensurately to maintain adequate internal volume. Again, note that Cp and Cx could also be varied in the effort to find a solution. At this point, weight and volume have been evaluated. Bear in mind that displacement weight must equal buoyancy, but that the available volume may exceed the required volume. If the available volume must exceed the required volume in order to provide sufficient buoyancy, this is an indication of a weight-driven design such as an Ore Carrier.

5.3.2.8 Stability check

The transverse metacentric height, GMt, is estimated to check initial intact stability. Note that initial stability at large heel angles and damage stability are evaluated at a later point in design when the required design detail is available.

To estimate GMt, estimate KMt and subtract KG, making a reasonable correction for tankage free surface (see Chapter 11 - Parametric Design). The two constituents of KMt, KB and BMt, are each estimated based on the known quantities L, B, T, Cp, and Cx, and the results summed. The transverse moment of inertia of the waterplane, It is estimated from the waterplane coefficient, CwoCw is estimated from Cp, recognizing that a transom stem significantly affects both Cw and It. GMt/B is computed and compared to a predetermined criterion of acceptability, generally ranging from 3 to 10%, depending on the ship type and its intended mission (lower for cargo ships, mid-range for passenger ships, and higher for warships). If the criterion is exceeded, the result might be accepted, at least temporarily; if the criterion is not met, corrective action must be taken. Either KG must be reduced or KMt increased. KG can be reduced by reducing D or deckhouse size or by lowering weights within the ship. At this early stage, reducing KG by lowering weights is not really feasible since individual weights have not yet been located within the hull. Reducing deckhouse size yields small gains and reducing D may be infeasible due to freeboard requirements or large object volume dimensions, for example, the required height of a low-speed diesel engine room. The most effective way to raise KMt is to increase beam since BMt varies as B squared, and this is generally the approach taken. Length may be reduced at the same time, if possible, to avoid excessive hull volume.

5.3.2.9 First estimate of propulsion power

The power required to propel the ship at the desired maximum or sustained speed is estimated. This estimate can be much improved over the Subsection 5.3.2.3 estimate since the hull dimensions and form coefficients are now known, along with a better estimate of ship displacement. Assumptions have been made regarding the general characteristics of the hull shape at the ends, for example, whether or not there is a transom or bow bulb. Bare hull resistance is estimated using one of the established techniques; for example, a standard series, a regression analysis, or test results of a similar hull. The principal hull appendages are identified, permitting an estimate of appendage drag to be made. Overall propulsive coefficient is estimated and shafting and reduction gear losses are accounted for (or electric losses in the case of an electric ship). The resulting required propulsive power is compared to the installed power assumed in Step 3 of Figure 5.6. If the installed power is equal to or somewhat greater than the required power, a tentative solution has been achieved. If the installed power greatly exceeds the requirement, it must be reduced. If it falls short of the requirement, it must be increased. In either case, the assumed propulsion plant must be modified and the process repeated, starting with Step 5. The revised propulsion plant is likely to have a revised engine room volume and hence the total required volume will change. If the fuel endurance is specified at a speed other than the specified maximum or sustained speed, the speed-power estimate in Step 9 will include the endurance speed so that a refined estimate offuel weight can be made. This is a common situation for fossil fuel naval ships that cruise much of the time at fuel-efficient speeds and spend very little time at high speeds.

This completes the description of the nine steps listed in Figure 5.6. Even if a tentative solution has been achieved in the first pass through the process, it may be repeated starting at the step described in Sub-sections 5.3.2.4 or 5.3.2.5, using more refined estimates for the various parameters. This greatly improves the quality of the study and reduces risk. Required volume, weight and KG are prime candidates for refinement.

An arrangement sketch must be developed in order to validate the tentative solution before the study can be accepted. As a minimum, an inboard profile and main deck plan view must be depicted. A typical transverse section through the ship's midbody would be the next priority. Even if it were not required for validation, the customer would want to see a sketch anyway. The term *sketch* is used deliberately. Detail is not desired, only a simplified outline of the hull and deckhouse boundaries and the principal internal subdivisions: decks and bulkheads. Large object volumes should be located and identified. The primary reason for the sketch is for the naval architect to ensure that a satisfactory ship arrangement can be developed within the selected principal dimensions. In profile, does the selected hull depth permit a satisfactory allocation of deck heights to be made with adequate space in the overheads to run distributed systems? Can the heights of large object volumes such as the engine room be accommodated efficiently? Does the selected hull length permit a satisfactory arrangement of main transverse bulkheads? Can the lengths of large object volumes such as the engine room and cargo holds be accommodated efficiently, considering the requirements for collision and after peak bulkheads? Can one or more deckhouses with the required total volume be satisfactorily located on the hull so as to provide proper alignment with the engine room below deck, for example? Is the main deck length (and beam) adequate to accommodate all of the required topside functions? The minimum length required to do this in naval ship design is referred to as the *stack-up length.* The stack-up length often sets the hull length in ships with cluttered topsides such as surface combatants or in ships with specific topside cargo stowage requirements, such as heavy lift ships or container ships.

After a practical arrangement sketch has validated the study, capital and operating and support (O&S) costs can be estimated. Risks also must be assessed. Unique aspects of performance, beyond the usual calm water speed and fuel endurance estimates, are sometimes evaluated, albeit in pre-time, it is important to remember that this is simply a starting point, and that all design decisions tentatively made at this point will be thoroughly reviewed later in the design process before they are *locked in.* The *decking out* process may require small changes to certain of the input parameters. The hull depth, for example, may be adjusted to provide the desired number of internal deck levels in an efficient manner, that is, without either inadequate or excessive *tween-deck* heights. Hull or compartment length might be modified slightly to equate to an even number of frames at the desired spacing.

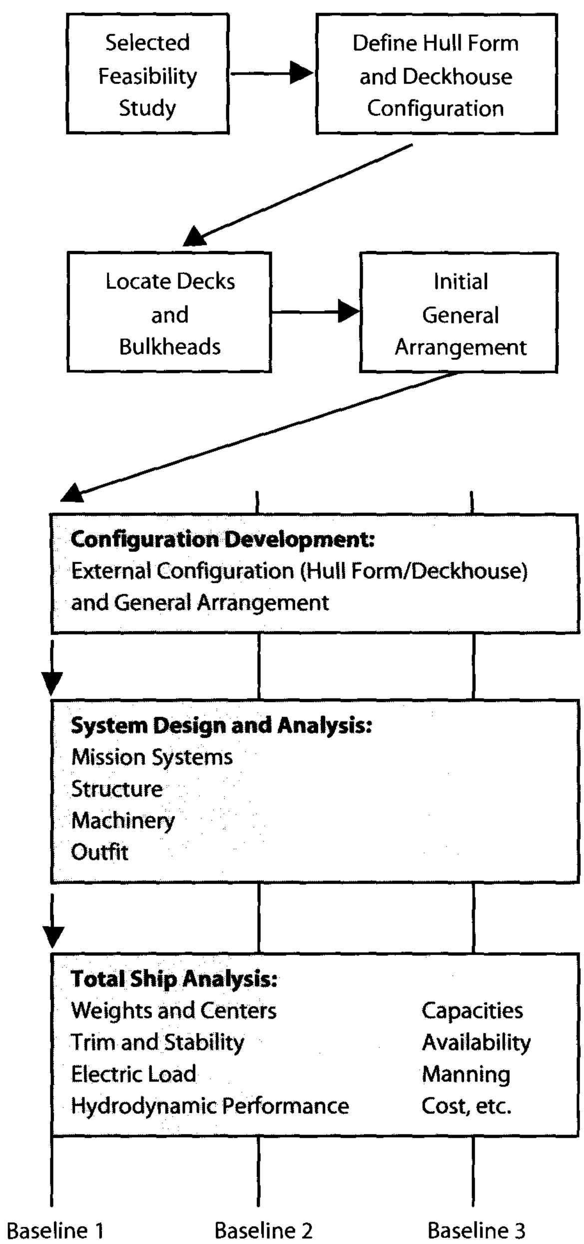

Figure 5.7 Naval Ship Concept Design Process

After the *decking out* process is completed, an initial general arrangement drawing is developed. The drawing depicts all so-called *large object volumes* such as the engine room and cargo holds. These are spaces whose heights are greater than a single normal deck height. Smaller spaces with normal deck heights are not individually defined at this point. Rather, blocks of space are allocated by function, for example, crew living, office and administrative spaces, navigation and other ship control spaces, workshops, etc. In the process of defining the initial general arrangement, it may be necessary to modify deck or bulkhead locations or even the deckhouse boundaries.

After the initial hull envelope and general arrangement have been defined, parallel design development can proceed in a number of functional areas, as depicted in Figure 5.7. The parallel design development effort extends beyond the concept design development and, in fact, continues through all the remaining design phases. The ensuing design development activities can be classed as design and analysis activities, as depicted in the figure. As system design and total ship analysis proceeds, conflicts with the initial hull envelope and/or the general arrangement will be identified and must be resolved. Resolution may necessitate changes in either the hull envelope or the general arrangement. For example, development of the propulsion plant, including the initial machinery arrangement, may indicate the need to lengthen the engine room, which in turn will require a change to the general arrangement.

Figure 5.8 is a depiction of the concept design task categories after the initial configuration definition (Baseline 1 in Figure 5.7). Additional detail is provided. There are strong interactions between both the ship envelope and the general arrangement and three of the eight areas of system design activity noted in the figure. These are structures, propulsion plant and mission systems. Similarly, there are strong interactions between most of the areas of system design activity and the eight analysis activities noted in the upper block of total ship analysis tasks. For example, most areas of system design will contribute products to the area/volume analysis, the weight estimate, the electric load estimate, and the Master Equipment List (MEL). The topics listed in the second block of analysis tasks have equally strong interactions but with fewer system design tasks. There are strong interactions between both the hull form and the weight estimate and the hydrodynamic performance and stability analysis tasks. The general arrangement also has a strong interaction with the damage stability analysis task. Noise and vibrations analysis tasks are strongly linked to the general arrangements and to the principal noise sources: propulsion and other rotating machinery and the propulsor itself. Fuel weight and volume are linked to the required propulsion power at the endurance speed, as well as to the efficiency of the propulsion and electric power generating plants at that speed.

As design development proceeds, interim products are produced in each of the system design and total ship analysis task areas and fed to other areas that use them as inputs or as information updates. Frequently, updated information will reveal problems or *disconnects* in the design that the team must set to work to resolve. For example, the damage stability analysis may reveal the need to change transverse bulkhead spacing at the after quarter point which is at odds with the general arrangement. Such disconnects cannot be predicted in advance and the skill of a design team may be measured by how quickly they can be identified, addressed and satisfactorily resolved.

Figures 5.7 and 5.8 are generic in that they are applicable to the entire system design process once the initial hull envelope and general arrangement have been defined. In concept design, not all of the tasks identified in Figure 5.8 will be performed; others will receive varying degrees of attention, depending on the design problem at hand.

Tasks emphasized are those with the major influence on overall ship size, cost, performance and risk. Examples of tasks not performed in concept design might include the availability, noise and vibrations analysis tasks. Tasks given minimal attention might include the manning analysis task and the following design tasks: Outfit and Furnishings (O&F), fluid systems, HVAC system, and auxiliary machinery/mechanical systems. For concept design, there is insufficient detail to develop a manning estimate based on workload considerations. It would be premature to spend much effort defining O&F details. Design effort in the systems task areas mentioned above might be restricted to selecting a reasonable baseline system concept, describing it by means of a highly simplified I-line diagram and, for that concept, identifying major system components and estimating their sizes by ratiocination from similar ships.

5.4 DESIGN DEVELOPMENT

In this section, the design development process, subsequent to the development of an initial concept design, is discussed. This process occurs during the preliminary, contract and functional design phases.

5.4.1 Overview

The design development process is a parallel one, performed by persons with expertise in the various design disciplines. These persons develop their portions of the design in parallel, exchanging data at appropriate points in the process. The initial concept design provides the data that is needed to start this parallel development process. It is the initial design baseline. The design development process generally reflects the classical systems engineering process with two principal objectives: to optimize the total ship system at the expense, perhaps, of individual subsystem optimization, and to address production, operation and support aspects too often neglected, for example, producibility, reliability, maintainability, supportability, operability, life cycle cost and human systems integration (manpower, personnel, training, safety and health hazards).

In each design discipline, the development process consists of the following generic steps: requirements derivation, synthesis of alternative concepts, evaluation of the concepts, selection of the preferred concept, and further development of the selected concept. This may lead to the exploration at finer levels of detail of additional alternatives for elements of the parent concept. Thus, after the initial requirements derivation, the process consists of a trade-off study followed by design development effort. This cycle may be repeated several times before the design is fully developed.

The development effort in each discipline is referenced to the overall ship design baseline in order to keep the overall effort on track. The design baseline represents an integrated total ship design, at the level of detail to which the design has been developed. Periodically, the design baseline is updated and reissued to the design team. The updated baseline reflects interim design decisions, which have been made in the various disciplines as result of the ongoing trade-off study and design development process.

The design team leadership must ratify all such decisions before they are incorporated into the baseline. Several design baselines might be developed and issued over the course of a single design phase. As noted in Figures 5.7 and 5.8, some design development tasks are purely analysis tasks. These are referenced to the current design baseline. The orderly process outlined previously is disrupted when design problems are identified which involve more than one design discipline. The affected design disciplines must work together quickly and efficiently to solve such problems and minimize the disruption to the overall development process.

5.4.2 Trade-off Studies

Trade-off studies are an essential element of the design development process. The challenge is deciding which design issues must be subjected to a formal trade-off study and for those, deciding when the study should be done and to what level of detail. Design issues can be categorized in various ways, including:

- impact on ship cost, performance, and/or risk,
- impact on ship size and/or configuration, and
- multi-discipline vs. single discipline.

Issues that have a major impact on ship cost, performance or risk should be dealt with early in the process whil~ issues with lesser impact can be deferred. It makes sen~ to do this since studies done too soon may have to be reworked if there are significant changes in the design baseline. Issues with a significant impact on ship size and/or configuration must be dealt with at the total ship level, that is, these impacts must be evaluated. Issues with little or no impact on overall ship size or configuration can be dealt with at the individual system level. Issues with significant impacts can be subdivided further into those with effects so dominant that they require alternative ship concepts to be developed and evaluated vs. those whose impacts can be assessed without deviating from the baseline ship concept. Some issues can be studied by a single design discipline while experts representing several disciplines must address others.

In planning and executing the design development process, these categories should be considered and greater attention given to the more important ones. In general, the highest priority should be given to multi-disciplinary studies with significant ship size and/or configuration impacts. These studies should be planned in greater detail and performed as early in the process as possible. By so doing, the overall efficiency of the design process is maximized and the chances of major downstream perturbations of the design baseline are minimized. Formal trade-off studies are necessary to achieve a near-optimum design solution but they require time and resources. Thus the number of such studies undertaken must be tailored to the available design time and resources. A few studies of critical issues done well are always preferable to many mediocre studies of lesser issues. The shipowner will often identify specific issues that he wishes to see formally studied. The products of a trade-off study of several design alternatives should typically include the design requirements, descriptions of the alternatives, and estimates of the following attributes for each alternative, relative to the design baseline: design and engineering cost, if there are significant differences, procurement cost, operating and support cost, weight, space, electric load, manning, reliability, maintenance requirements, support requirements, training requirements, operability, risk (technical, cost and schedule) and pertinent aspects of performance, such as speed or seakeeping. The list of attributes to be evaluated is tailored to suit each trade-off study (see Sub-Section 5.1.9).

The recommendation of each completed trade-off study must be reviewed and approved by the leadership of the design team before it can be incorporated into the next update of the design baseline.

5.4.3 Design Integration

Total ship optimization is the primary purpose of design integration. Other objectives are to:

- ensure ship feasibility,
- satisfy the shipowner's requirements and constraints, and
- facilitate ship construction.

An optimized ship design is a *balanced* ship design. A balanced design is not optimized at the system or sub-system levels, that is, *give and take* has occurred between elements of the design. An optimized total ship will typically not have optimized systems and sub-systems.

In this regard it may be useful to view the ship as comprising different levels. Level I is the total ship. At Level II are the major ship systems such as hull, machinery, mission systems, etc. Level III comprises elements or sub-systems such as structure, propulsion, electrical, control, communications, and auxiliary machinery. Level IV consists of components such as prime movers, generators, reduction gears, shafting, and propulsors. Design integration is normally focused on the interfaces between elements at Level III and below.

Interfaces are classified as either functional or physica1. Functional interfaces refer to the service transfers between various functional elements of the ship (electric power, cooling water, communications, data, etc.), while physical interfaces refer to the spatial relationships between ship elements. Functional interfaces are most critical during the early design stages and must be resolved by the start of functional design. Physical interfaces are dealt with at all stages of design, but receive the most attention in the later stages of design, when issues such as alignment, physical support, interconnection, and routing are addressed in detail.

Six critical areas receive special attention during the design integration process. They are:

1. weight vs. buoyancy and draft, freeboard, trim and list,
2. stability,
3. hull girder strength,
4. space balance; that is, required vs. available internal volume, and deck area,
5. ship energy balance; that is, required vs. available energy of each type (electric power, steam, compressed, air, cooling water, etc.), and
6. ship control; that is, the interfaces between the ship control system and every dynamic functional element of the ship.

Ship design is performed by engineers and designers, typically organized along functional lines. Elements of the organization are responsible for elements of the design. Thus there are organizational interfaces that are related to the interfaces between ship system elements. Certain principles must be adhered to when organizing for ship design if design integration efforts are to be effective. They are:

- assign responsibility for complete functional elements to a single, lowest-level organizational unit,
- assign responsibility for closely interacting functional elements to a single organizational unit,
- distribute responsibility evenly between organizational elements,
- assign a manageable number of organizational elements to anyone supervisor,
- establish one organizational element responsible for whole-ship characteristics (tests and trials, manning, RMA, safety, cost, etc.) and for system engineering of areas which cut across several organizational elements, for example, ship control,
- staff with a high percentage of competent and experienced engineers and designers,
- keep the total design organization small, and
- avoid the introduction of organizational elements whose sole responsibility is the review of another organizational element's work.

The first two principles avoid introducing organizational interfaces where hardware interfaces do not exist. The next two principles assure a manageable workload for the various levels of supervision so that decisions involving system compromises can be made in a timely and efficient manner. The fifth principle assures proper attention is given to the total ship system characteristics. The last three principles are necessary for efficient performance.

An experienced design team will effectively address their interfaces with a minimum of direction and control from management and, the smaller the number of personnel involved, the fewer will be the number of communication channels and the more effective will be the exchange of interface data. Frequent, rapid and effective communications are a key to efficient design integration. Communications are essential, and a challenge. A collocated design team facilitates communications. Modem communication techniques permit *virtual collocation* of the members of a widely dispersed design team. However, virtual collocation is unlikely to ever equal the effectiveness of face-to-face exchanges of data and opinion.

In the initial concept design phase, the design team is small and communications are frequent and informal. The individual team members perform design integration as they work. Integration is an interactive and iterative function, and this is facilitated during concept design when the design team is small and, normally, collocated. As the design proceeds through preliminary and contract design, the integration function is no less important, but proves more difficult. Integration is important because during these phases decisions will be made on systems, sub-systems, and possibly even equipment that will determine the cost and performance of the ship. The integration function is more difficult because as the design matures it becomes more detailed and complex and, as a result, the size and diversity of the design team grows. For a complex warship, it has been estimated that as many as 40 different engineering disciplines ultimately may be involved, although not all on a continuous basis.

For complex ship designs, it is, therefore, common to create and empower a Design Integration Team (DIT) in the preliminary design phase or shortly thereafter. The DIT is focused on total ship design integration and its members are dedicated to that task. Typically, the DIT is staff to the ship design project manager and is empowered to act in his/her name. The members of the DIT are typically senior engineers with broad experience and with a total ship perspective. Collectively, their experience covers the full scope of topics and issues to be addressed during the design. Specialists in the functional design organization perform synthesis, analysis and trade studies. The DIT's objective is to achieve that combination of subsystem features and performance that provides the *best* or optimum combination of total ship cost, performance and risk, within the bounds of economic and technological constraints. In some engineering organizations the functional groups are quite strong and independent, and resist oversight and direction. This has led to unbalanced ships where one function or element has been emphasized at the expense of others. The key is to make all decisions on what is best for the *total ship.* The DIT must be empowered by top management to make the tough decisions. And, of course, they must serve as honest brokers.

5.4.4 Design Planning and Control

The objectives of design integration have been described as well as its nature. The concept of the Design Integration Team has been introduced. Turning now to the design integration process, it can be described as three sequential activities for a specific design phase. These are up-front planning, in-process control and formal reviews at the end of the phase.

5.4.4.1 Planning

The first and perhaps most important activity is proper planning of the design phase. Many designs are started on a casual, ad hoc basis and there is little or no opportunity for formal planning. For each subsequent phase, however, formal planning before the start of the phase is essential. The work effort in each task area must be defined, including the approach to be taken, the inputs required from other task" areas, the deliverables or products to be created, the wor~. schedule, including the dates for inputs, outputs and intermediate milestones, and finally, the labor hours and resources required. Resources could include computers, facilities, funds for model construction and testing, etc. The DIT must take the lead in creating an overall, top-level design schedule. This must address intermediate project milestones at which the design baseline will be formally updated, as well as the dates for major reviews of the entire ship design. The individual plans for each task area must be integrated with this overall plan and with each other. Emphasis must be placed on the interfaces between the various functional elements. These interfaces must be identified and recognized by the affected parties on both sides of the interface. The dates for the exchange of interface data must be scheduled such that there is sufficient time to complete the de-" sign of the affected elements of the design. The DIT must identify major design issues that can only be addressed by the joint action of two or more functional areas. The DIT must lead the effort to develop action plans to address these issues and see that they are incorporated into the overall design phase plan. The DIT must also ensure that the design phase plan includes the effort to produce the design products that that it needs to do its job.

5.4.4.2 In-process control

The second design integration activity is in-process control. The DIT plays a key role in controlling the effort of a large design team. The DIT continually assesses the developing design, but periodic meetings and design reviews are held as well. Minutes are taken and action items assigned and followed up. The DIT can employ several design controltechniques. One is to formally update the design baseline at regular intervals during a lengthy design phase. A six-week interval is typical. The interval can be shorter for smaller teams and those working to an accelerated overall schedule. Formal updates of the design baseline help to keep all members of the design team working on the same design. They also serve to keep the current design baseline relatively up to date and reflective of recent design decisions, made since the previous baseline *refresh.* This reduces the amount of rework that must be done by the design team members as they shift their own work to the new baseline. If the update interval is too short, team members must stop work and shift to the new baseline too frequently. If the interval is too long, team members spend too much time working to a badly outdated baseline. Shifting to the new baseline when it is finally issued is a major task and too much costly re-work is required.

Another control technique is to require formal approval of changes to specific elements of the design baseline such as the lines drawing, the general arrangements or the Master Equipment List (MEL). Since the MEL can go down to a very detailed level such as the 5-digit Extended Ship Work Breakdown Structure (ESWBS) level, and is constantly changing, formal approval should be reserved for the *big-ticket* items. The hull lines and the deckhouse or superstructure configuration define total internal volume. The general arrangement drawing or 3-D arrangement model defines the subdivision and spatial arrangement of the ship's enclosed volume. These drawings can be used to control overall ship size and internal arrangement by controlling the changes made to the drawings as the design is developed. The design team leader may delegate change control authority to the DIT or may retain this authority but look to the DIT for its recommendation on each proposed change. The power to control changes must be exercised judiciously. Two important issues are when to apply formal change controls and what features or parameters should be controlled. If formal controls are applied too early in the design effort, they can stifle innovation, burn up valuable resources in managing the effort and destroy design team morale. Morale plummets if it becomes too difficult to get approval of straightforward changes intended to improve the design or solve a recently discovered problem such as a physical interference. On the other hand, later in the design process, formal configuration control procedures become mandatory to avoid the devastating ripple effects if one person or functional group unilaterally makes an ill-advised change without adequate consultation with design management and the other affected parties.

Design resources can be controlled to some extent by a technique called *design budgeting.* For example, the DIT might establish a light ship weight budget with each element assigned to the functional area with cognizance, such as, structure, propulsion, O&F, etc. Each functional area is then tasked to attempt to stay within their allocated budget as the design is developed. The estimated or calculated weight is compared to the budget value at regular intervals and the trend is tracked over time. This approach also can be employed with other design parameters such as electric power load and other support services, system availability, and manning. The collected trend analysis results for each parameter are updated and distributed among the design team on a regular basis. The allocated budgets for any parameter can be modified with or without increasing the overall budget, if during design development it becomes clear that re-allocations are indicated. This technique is useful for sensitizing the design team to the importance of certain design parameters and for enlisting their aid in efforts to meet the overall goals. On the other hand, if the approach is;applied too rigidly, a great deal of work can be wasted in futile efforts to reach an unobtainable goal. In the case of attempts to save weight, this not only wastes engineering effort but also generally drives up ship cost as well since lighter weight systems and materials generally cost more.

A very effective control technique is the in-process design review. At these informal reviews, the individual responsible for a specific element of the ship design presents the design approach, status and current design configuration. A typical design review agenda is shown in Table 5.V!. In attendance are the DIT and other members ofthe design team responsible for the design of elements or subsystems that interface with the element under review. Frequently, misunderstandings regarding the interfaces between elements are identified and resolved on the spot; in some c~ses, the design approach is modified as a result. The DIT has the opportunity in such reviews to verify that the subject design effort is *on track* and that no attractive design options are being overlooked.

During the design development process, unanticipated

TABLE 5.VI Design Review Agenda

Major design requirements
Trade study results (if applicable) and documentation
Area/volume requirements (vs. space allocations)
Compartment arrangements
One-line diagrams
Performance analysis results
Specifications status
Status of MEL inputs
Cost (current estimates vs. allocations - design, construction, O&S)
Manning (current estimate vs. allocation)
Weight (current estimate vs. allocation)
Producibility considerations
Test and Validation requirements and status
Risk assessment and status
Logistics support
Reliability, maintainability, and availability
System safety
Status of formal deliverables
The way ahead (plans to complete work)
Review of assigned action items

technical problems are often identified that must be promptly addressed by the design team. When these problems involve issues within the purview of more than a single organizational unit, the DIT is chartered to take the lead in seeking a solution. Oftentimes, an ad hoc working group (sometimes called a *tiger team)* is formed if the problem or issue is particularly complex. Members are drawn from the organizational units most directly affected by the issue. Engineering effort may be required to synthesize and analyze one or more alternative solutions to the problem.

The DIT must quickly develop a plan of action in concert with the affected parties and then manage the resulting study in parallel with the on-going mainstream design effort. The study results must be reviewed before a recommendation as to the best resolution can be made.

The preceding discussion of the design integration process is primarily applicable to the system design phases through contract design, when the focus is on the identification and resolution of functional interfaces. Physical interfaces are addressed in the early design phases also, but at a fairly high level, in terms of space, weight and support services requirements. Space assignments, adjacencies and access requirements are addressed via the general arrangements drawing. One-line diagrams define support services. In the functional design phase, the focus turns to physical integration, which must be addressed in comprehensive detail. During functional design and beyond, two major activities occur. One is the development of assembly and installation (A&I) details, that define how each piece is mated with another, for example, a stiffener to the adjacent plate, or a piece of equipment to its foundation. The other activity is the entire process of physical integration. The A&I details are important to the shipbuilder but the physical integration process is a much greater challenge to the design team. This process concerns the arrangement of all the items in an area or zone of the ship so as to optimize performance, producibility and cost, as well as eliminate all interferences. Typical items in a zone are structure, joiner work, insulation, distributive systems (for example, power cable, vent ducts and piping), equipment, furniture and other outfit items. To remain competitive, it is mandatory that an efficient physical integration process be employed.

Traditionally, 2-D drawings and physical models and mockups have been used to support the task of physical integration and to document its results. Today, computer-based 3-D geometry models are replacing these techniques.

Overlay drawings are transparent, multi-sheet, plan view drawings for a control area showing the deck arrangement, overhead structure, lighting arrangement, and the optimum run for each distributive system. The sheets are overlaid and then combined by an experienced team composed of experts in each discipline. These experts optimize the combined· system designs, eliminating interferences in the process: The product is a single master overlay drawing for the control area. Hole control drawings are the results of a procedure implemented during detail design to ensure that the structural penetrations required to run distributive systems do not impair the strength of the hull and superstructure.

Composite drawings are another means of performing physical integration. A composite drawing is a single drawing showing all of the system runs, equipment and other obstructions in a control area in multi-views. The master overlay drawing described above is a single view composite drawing. Composites are more accurate than overlays but overlays are simpler and can be produced more quickly and cheaply. On some designs, composites are used selectively to supplement the overlays in particularly important and congested areas. The Interface Control Drawing (ICD) depicts selected features of two or more interfacing items to ensure compatibility between and among them. ICDs are developed after a local area has been designed to control the resulting configuration. The ICD permits subsequent design activities to proceed independently and concurrently with assurance that the specified interface previously agreed upon is adhered to. One example of an ICD is a drawing of a section of deck structure showing the distributive system penetrations. The ICD defines the physical interface between the distributive systems in the area above the deck and those in the area below. Another ICD example is an Outline and Mounting (O&M) drawing that defines the physical interfaces between a piece of equipment and its foundation, support system connections, and adjacent ship structure, joiner work, equipment and other systems.

Physical models and mockups are built when drawings are not considered to be adequate for full evaluation and physical integration of the design. These situations are typically portions of complex, high value ship designs that are especially congested, such as the propulsion machinery rooms, Navigation Bridge, and ship control spaces.

As was previously mentioned, today the drawings and physical models and mockups described above are giving way to the computer-based 3-D geometry model. As the design team develops the physical details of the design, they are captured in a single 3-D model that steadily grows in complexity. Members of the design team can view the model at any time and from any point of view. The computer can be programmed to identify and flag each physical interference to facilitate their elimination by the design team. *Slicing* the 3-D computer model with any desired intersecting plane can readily produce any drawing mentioned previously.

5.4.4.3 Formal design review

The third and concluding activity is a formal design review performed at the conclusion of the design phase. During this review, all elements of the ship design are scrutinized to ensure that they are complete, fully integrated, and collectively describe a ship design that meets the shipowner's requirements, is producible, and is economically viable. The DIT plays a leadership role in the final design review. If a specification is included in the design deliverables, it is also carefully reviewed for completeness, technical accuracy, and consistency, both internally and with other elements of the design package. After the specification has been completed, it is distributed to all concerned parties for their individual reviews. Comments are collected, collated and again distributed to all concerned. Finally, a reading session is held to which all parties are invited. At the reading session, the comments received on each specification section are reviewed and consensus is reached on the disposition of each. Failing consensus, the design team leadership will make the decision. To save time, when a difficult issue is identified, it is assigned to an individual and taken *off-line* for further consideration of the comments received, debate on the issues, and development of a specific recommendation. The recommendation is then brought back to the reading session for final discussion and approval. The recommendation may necessitate changes to other parts of the design package. A specification reading session typically lasts for several weeks. The time is well spent, however, since the session is an invaluable opportunity for everyone with a vital interest to voice their concerns and also hear the concerns of others. The resulting specification and design package is greatly improved by this interaction.

5.5 DESIGN TOPICS

The ship design process is undergoing significant change. This includes the adoption of new tools, new processes, and new management practices. These trends are briefly discussed in this section. Some are essentially *stand alone* topics, but others describe approaches that build upon and support each other.

5.5.1 Systems Engineering

5.5.1.1 Description

Systems Engineering (SE) is a formal process for the design of complex systems to meet technical performance and supportability objectives within cost and schedule constraints. The SE process involves both technical and management aspects. Its principal objective is to achieve the optimum balance of all system elements so as to optimize overall system effectiveness within cost and schedule constraints, albeit at the expense of sub-system optimization. The SE process transforms an operational need into a.completed system design employing an iterative process of functional analysis, design synthesis, system analysis, evaluation and decision, and system documentation. Per the International Council on Systems Engineering (INCaSE), as quoted in Table 2 of reference 9, the SE process focuses on defining customer needs and required functionality early in the development cycle, documenting requirements, and then proceeding with design and system validation. The SE process integrates related system technical elements and ensures the compatibility of all physical, functional, and program interfaces. The SE process embraces technical disciplines that cut across the traditional functional discipline boundaries as key elements of the total engineering effort. These disciplines include: reliability, maintainability, supportability, safety, manning, human factors, survivability, test engineering and production engineering. During system development, the SE process gives great weight to customer needs, characterizing and managing technical risk, transitioning technology from the R&D community into the system development effort, system test and evaluation, system production, and life cycle support considerations.

Per reference 10, the objectives of the SE process are:

- ensure that the system definition and design reflect requirements for *all* system elements: hardware, computer software, personnel, facilities, and procedural data,
- integrate the technical efforts of the design team specialists to produce an *optimally balanced design,*
- provide a comprehensive indentured framework of system requirements for use as performance, design, interface, support, production and test criteria,
- provide source data required to produce and test the system,
- provide a systems framework for logistic analysis, *integrated logistic support* (ILS) trade studies, and logistic documentation,
- provide a systems framework for production engineering analysis, producibility trade studies, and production/manufacturing documentation, and
- ensure that life cycle cost considerations and requirements are fully considered in all phases of the design process.

It should be noted that reference 10 is the source of much of the information presented in this section.

5.5.1.2 History

The development of formal SE processes is linked to the development of increasingly complex systems utilizing advanced technologies and incorporating human operators as well as computers in analysis and decision-making roles. Increased system complexity has increased emphasis on the definition of requirements for individual system elements as well as definition of the interfaces between system elements. A formal hierarchy of linked requirements is developed, spanning the gamut from top level total system requirements down to requirements for the smallest elements of the system. Increased system complexity has also seen an explosion in the effort required for computer software development relative to hardware development. Today, the software development effort for complex systems may equal or exceed the hardware development effort. Increased system size and complexity has forced expansion of the engineering workforce required to develop and field the system, as well as increased specialization within the workforce. Collectively, these trends have inevitably forced the managers and integrators of complex systems to expand and formalize their development procedures and processes under the *systems engineering* umbrella.

The origins of SE go back to well before WW II. However, the SE process for the development of complex systems was first formalized in the mid-1950s in connection with US Government ballistic missile programs. MIL-STD-499 was issued in 1969 to provide guidance on SE principles and processes to the US defense industry. MIL-STD-499A, issued in 1974, has been a foundation document in the development ofthe field. INCaSE was formed in 1990 to support SE practitioners with guidance documentation and sponsorship of workshops and symposia for the exchange of innovative ideas. MIL-STD-499B was drafted in 1994 but never issued. In its place, EIA/IS-632, an interim commercial standard, was issued in June 1994. This document has since been formalized and issued in Jan 1999 as EIA-632.

5.5.1.3 Process

The SE process is, in fact, a collection of processes. There is a fundamental process, almost a philosophy, which is surrounded and enhanced by a number of other processes that complement or focus on particular aspects of the fundamental process. Examples are processes for risk management and requirements development and allocation. The fundamental SE process is depicted in Figure 5.9.

The process is iterative; it is repeated in increasing detail in each phase of the system development. The fundamental process is also utilized by many elements of the design team in parallel. It is followed at the total system level by those with overall responsibility for system integration while, at the same time, it is being followed by the developers of individual subsystems, elements and components. Remember that one person's system is another person's subsystem! The principal steps in the process are shown in the figure. Each step is briefly discussed below.

Initial Requirements: Initial requirements are needed tQ start the system development process. Typically these requirements are contained in an initial draft system requirements document. They reflect an operational need and consist of mission objectives, environments and constraints, and the relevant measures of effectiveness for the new system.

A detailed description of how these initial requirements are developed is beyond the scope of this discussion. Generally they come from the customer for the system with major inputs from the operating forces that are potential system users.

Functional Analysis: Functional Analysis (FA) is a method for analyzing the initial top level requirements for a new system and dividing them into discrete tasks or activities. FA defines the essential functions that the system must perform based on the system mission requirements. FA consists of two activities: the identification of system functions, and the allocation of system requirements. FA is performed in parallel with the second step in the fundamental process, design synthesis, since there must be interactions between the two activities. FA starts with the

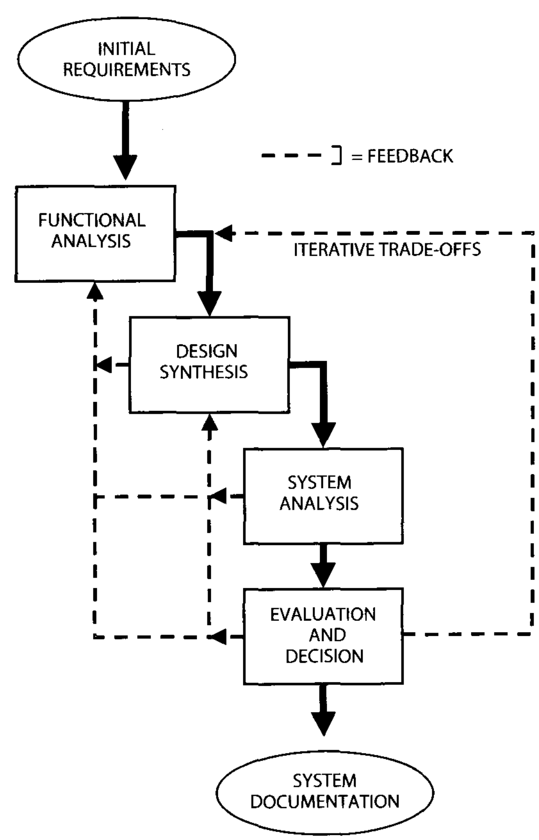

Figure 5.9 The Systems Engineering Process

identification of the top level system functions and then progressively allocates the functions to lower levels in the system, for example, each top level function is subdivided into several second tier functions, each of which is further subdivided, and so on. There is a dramatic increase in the number of functions to be performed at each lower level. A decimal numbering system, applied to each function, is used to maintain traceability between the functions identified. There are five system element types: hardware, computer software, facilities (for production and service life support), personnel, and procedural data. Each identified function is assigned to one element or to combinations of elements. Each function is described in terms of inputs, outputs, and interface requirements. *Functional Flow Block Diagrams* (FFBDs) are used to document the results of function identification. The FFBD depicts the sequential relationship of all the functions to be performed at one level, that is, the time-phased sequence of the functional events. Some functions can be performed in parallel and this is reflected in the diagram. The FFBDs are developed at several levels. A single function block at Level 1 is subdivided into many blocks at Level 2. For some time-critical functions, time line analysis is used to support the functional analysis and design requirements development.

Requirements Allocation: Requirements Allocation (RA) proceeds after the system functions have been identified in sufficient detail and candidate system design concepts have been synthesized. RA defines the performance requirements for each functional block depicted in a FFBD and allocates the functional performance requirements to individual system elements (hardware, computer software, personnel, technical manuals, or facilities). The performance requirements are stated in terms of: 1) purpose of the function, 2) performance requirements, 3) design constraints, and 4) requirements for aspects such as reliability, human performance, safety, operability, maintainability, and transportability. RA decomposes the system level requirements to the point where a specific hardware item, software routine, or trained crew member will fulfill the needed functional/performance requirements. RA is complete when further decomposition of the functions/tasks does not result in additional requirements for hardware, software, facilities, or personnel. Supporting analyses and simulations may be required to allocate system level requirements. RA is the logical extension of the initial functional identification; it is generally done prior to completion of preliminary design.

The end result of RA is the system specification and lower tier specifications. RA results are documented using a Requirements Allocation Sheet (RAS) or the equivalent commercial computer software. Both performance and design requirements are captured in the RAS, which has a flexible format. Performance requirements may be qualitative or quantitative. The personnel requirements for all tasks are defined. Design constraints such as dimensions, weight, and electric power are defined and documented in the RAS, along with all functional and technical interface requirements. Some performance requirements or design .constraints can be allocated to lower levels of the system, for example. weight. A technical budget is established when a design or performance parameter is allocated among the system elements.

Design Synthesis: Design synthesis is sometimes called *conceptual design.* It provides the engineers' response to the requirements outputs of functional analysis. Its goal is the creation of a system or design concept that best meets the stated system requirements. Technology options are combined in a creative process that is constrained by the laws of physics. Inputs from all functional areas (enginee~ng specialties) that significantly affect the result are utilized. Typically, several possible technical approaches are postulated and, for each approach, several system concepts. For each system concept, several design concepts are typically synthesized and assessed. Two tools are used to document the resulting candidate design solutions, that is, the overall configuration, internal arrangement of system elements, and principal attributes of each design concept: the *Schematic Block Diagram* (SBD) and *Concept Description Sheet* (CDS). SBDs define the functions performed by the system and the interfaces between system elements. As the concepts that survive the screening process are developed further, SBDs are developed in greater detail. Ultimately, they are used to develop *Inteiface Control Documents* (ICDs). For attractive design concepts, physical and analytical system models are developed later in the synthesis process. These models are used to support the subsequent system analysis by means of simulations, for example. The CDS is the initial version of the Concept Design Report, a technical report that documents the completed concept design. This report includes drawings and technical data such as weights, MEL, etc. The results of system analysis for the concept, described next, are also typically included in the report.

System Analysis: Once a design concept has been synthesized, its mission effectiveness (overall performance), costs and risks are analyzed. The assessments may be either quantitative or qualitative, depending upon the attribute being analyzed, the number of candidate concepts, and the extent to which the concepts have been defined. As the design development proceeds, the number of attributes analyzed and the sophistication and level of detail of the analyses will tend to increase. Early phase analysis typically consists of quick quantitative assessments using empirical data based on past designs and reflects many simplifying assumptions. For a few critical aspects of performance, more detailed qualitative assessments might be made. In the later stages of development, much more sophisticated modeling and simulation is done, coupled with physical model tests in some cases. It is often very difficult to evaluate overall mission effectiveness for complex, multi-mission systems. Instead, the aspects of performance with major effects on mission effectiveness are identified and analyzed individually. Development, production and operation and support (O&S) costs are typically analyzed for each option being considered. Risk is assessed using standard procedures. Two parameters are evaluated: first, the probability that a failure might occur, and second, the potential impact of that failure.

Evaluation and Decision: Trade-off studies are an essential part of the systems engineering process. Once several alternative design concepts that satisfy a set of requirements have been developed and analyzed, the results of the analysis must be evaluated and a decision made. This is typically done using a standard trade study methodology that provides a structured analytical framework for evaluating a set of alternative design solutions (candidate concepts). There are seven steps in the standard methodology as discussed in reference 10. Each step is briefly described below.

- Step 1: Precisely define the objectives and requirements to be met by the solution candidates (the Functional Analysis step described previously).
- Step 2: Identify the solution candidates and screen out the obvious losers (Design Synthesis).
- Step 3: Formulate selection criteria and, if possible, define threshold and goal values for each (minimum acceptable and desired values, respectively).
- Step 4: Weight the criteria. Assign numerical weights to each criterion according to its perceived contribution to overall mission effectiveness. Mathematical techniques can be used to factor in various opinions as to the preferred weights.
- Step 5: Prepare utility functions. This is a good technique for translating diverse criteria to a common scale, for example, comparing speed vs. endurance vs. cargo capacity vs. on-off-Ioad times for a sealift ship. The utility score for each criterion varies from 0 to 1, representing the threshold and goal values, respectively. The utility function is a curve on a 2-D plot; a notional example is shown in Figure 5.10. The shape of the curve must be defined based on a judgment as to the relative value of incremental performance improvements at various points in the threshold to goal range.
- Step 6: Evaluate the alternatives. Estimate overall performance and other required attributes such as risk (System Analysis). Then score the overall mission capability vs. cost. Calculate the cost/capability ratio (or its in,-verse) for each alternative ..
- Step 7: Perform sensitivity analysis. Assess the sensitivity of the resulting overall score to changes in criteria, weights, and utility functions. This enables a more ip.-formed judgment to be made as to whether one alternative is clearly preferred over the others.

System Documentation: The system design must be documented as it evolves. Traditionally, this has been done on paper by means of documents such as specifications, drawings, technical reports, and tables of data. Today, this is increasingly done utilizing integrated design systems and producing the desired documentation on CDs. In the future, Smart Product Models will contain all necessary design documentation; see Section 5.5.2.

5.5.1.4 Relationship Between Systems Engineering and Traditional Ship Design

van Griethuysen (11) has stated that:

> In many ways systems engineering is no more than a generalized model of, and framework for thinking about, the engineering process, which needs tailoring to be applicable to a particular product and project. It is, therefore, self-evident that marine products have always been designed and produced using a form of "systems engineering" even if those particular words were rarely used. It is also true that much of naval architecture and marine engineering concerned with design and management is undoubtedly an example of systems engineering.

It is true that the traditional ship design process is an example of SE and that naval architects designing ships are systems engineers. It is also true that the rigor of the SE

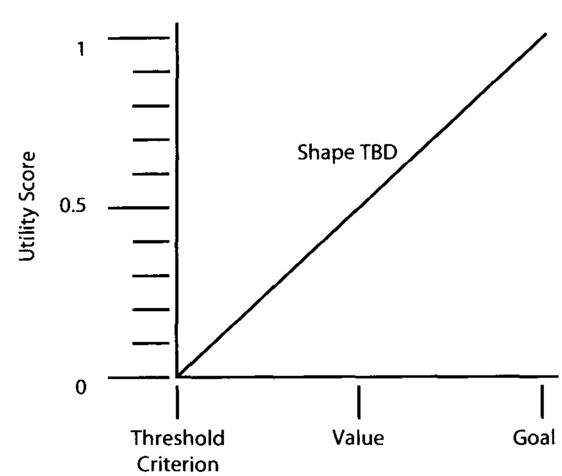

Figure 5.10 Sample Utility Curve

process is required to design a successful modern multi-mission warship or complex commercial ship such as a cruise liner, with all of its hardware, software and human factors complexities. The fundamental SE process differs from the traditional ship design process primarily in the functional analysis step, including requirements allocation, and, to a lesser extent, in the system analysis step. Naval architects have not traditionally performed a complete, rigorous functional analysis for each new ship design because it was not necessary. The ships being designed were not complex enough to warrant it; the functions to be performed, the associated performance requirements, and the links between these performance requirements and the system elements were well understood. Nor have naval architects traditionally performed the complete system analysis required for complex systems, including the formal and comprehensive assessment of overall mission effectiveness. The functional analysis and rigorous system analysis steps are second nature to combat systems engineers but are not as familiar to most naval architects and marine engineers. Naval architects and marine engineers who are members of the multi-disciplinary team designing a modern warship must understand and actively participate in these processes.

5.5.2 Concurrent Engineering and IPPD

Concurrent Engineering (CE) is the totally integrated, concurrent development of product and process design using collocated, cross-functional, empowered teams to examine both product and process. The essential tenets of CE are customer focus, life cycle emphasis, and the acceptance of design ownership and commitment by all team members. It reflects the view that design, whether it is art or science, should not occur in isolation.

CE, with its focus on consensus, has its greatest value for developing systems which require widest acceptance for their success, such as those that directly impact the survival of individuals. This success is also its greatest weakness resulting in *design by committee* and *groupthink.* It must be realized that CE is not a science but a human art, which cannot be quantified.

In the past in the U.S. there has been widespread emphasis on work specialization, and the result often has been a *stovepipe* organizational structure. These *walls* impede communications and the transfer of information. CE is not new; many of its techniques and tools have been around much longer than CE, but CE packaged them into an integrated philosophy. CE was *invented* to remove the walls discussed above. Its implementation, therefore, goes to the very structure of an organization and its management philosophy

Experience has shown (12,13) that CE cannot be implemented gradually and gracefully; an *all or nothing* approach is required.

Implementation of CE requires moving from:

- department focus to customer focus,
- directed individual or group to coached team,
- individual interests to team interests,
- autocratic management to leadership with empowered followers, and,
- dictated decisions to consensus decisions.

Such changes are clearly difficult to implement. They require the expenditure of time and money. Perhaps an even greater challenge is changing the culture of the organization. Top management must understand that CE is not a quick fix, but there are potential long-term benefits. CE is not *the flavor of the month.* Managers and workers at all levels may be fearful of giving up some individual authority, but they must recognize that change is necessary in order to remain competitive in a world economy.

Why then should CE be adopted? The primary benefit is improved design and production productivity and design quality (12). This can lead to increased market share. This is achieved by:

- understanding the customer's requirements, both qualitative and quantifiable, and the cost impact of satisfying these requirements (see Section 5.5.5).
- an objective appraisal of one's own (current) products and those of the competition (bench marking), and,
- minimizing the time (and hence the cost) from initial design through production and fielding.

A basic premise is that the ship designer has many customers. These include the shipbuilder who must take the products of design and turn them into a ship. It also includes those who will operate and maintain the completed ship through its service life. Experts on crew training and logistics are also *customers,* particularly ifthe design includes new technologies. Finally and *foremost,* the prospective shipowner/operator is a customer.

These different groups view the ship design from different perspectives. They have different goals and objectives, and they bring different experiences and expertise to the team. The basic premise of concurrent engineering is that the early involvement of *all* these different customers will produce a better product. Expressions such as Integrated Product Teams (IPT) and Integrated Product and Process Development (IPPD) are now widely discussed. The word *integration* is significant. Coupling process and product is also worthy of note, since it recognizes that if you hope to improve the product (the ship), you must first examine and improve the processes used to design and build the ship.

What then does the application of CE mean to the ship designer? In the past, ship designs were often developed by a *stove piped* design organization without the direct, early participation of the future ship's builder, shipowner, operators and maintainers. Nor were specialists in unique but important disciplines such as manning, cost, safety, reliability, and risk analyses involved from the outset. When these and other groups did get involved, after the design was largely complete, it was generally in a *review and comment* mode. By this time, changes would be difficult to incorporate without cost and schedule ramifications. In addition, an *us versus them* relationship might exist.

In contrast, a design team that employs CE principles also includes experts in:

- requirements analysis
- cost analysis (acquisition and O&S),
- the *!lities* (reliability, maintainability, availability),
- manning, including training,
- manufacturing/producibility (production engineering),
- material procurement,
- tests and trials,
- marketing, and
- in-service support.

A shipowner's representative is also a team member.

The basic premise of CE is that it is better to make design decisions (at all Levels) based on real time (or near real time) feedback from all who have an interest in designing, producing, marketing, operating, and servicing the final product.

This approach has a common-sense appeal, and CE, IPT, and IPPD have achieved a certain vogue in the US, within both industry and the Government. These approaches are adopted in order to get disparate groups to communicate better and thus to eliminate the *stovepipes.* They are, therefore, a means to an end. Of interest, some other shipbuilding countries have seen no need to take such measures, having a successful tradition of getting groups to work in concert without the need for formal, ad hoc CE teams.

The term concurrent engineering is sometimes confused with concurrent development. The latter primarily refers to warships where new systems (combat, weapons, and propulsion) may be developed simultaneously with ship design development. This presents a unique set of risks and challenges. If new, fully defined, systems are *frozen* too soon, they may prove to be obsolescent when the ship is completed years later, particularly electronic systems. Yet, if selection is delayed to permit the concurrent development and maturing of new systems, these systems may prove to be difficult to integrate when their ship impact characteristics (space, weight, kW, manning, etc.) are well defined. This topic, however, is beyond the scope of this chapter.

5.5.3 Collocation

The decision to collocate the design team should be nOn-controversial since it leads to better integration and coin-munications, and those intangibles such as teamwork, a sense of ownership, and esprit de corps. However, in a large engineering organization, many designs or products may be being pursued at the same time, and/or the functional engineering codes may have other tasks: Research and Development (R&D), In-service Engineering (ISE) for ships at sea or in overhaul, and *fire drills.* The argument against collocation is that dedicating resources to a single project would dilute the total available resources. Thus, collocation can only be justified for high priority, high visibility, or high-risk programs. Top management must resolve the benefits of, and the counter-arguments to, collocation as it sets priorities.

In the past, collocation referred to physical collocation and up to 100 percent dedication. While, it is believed that there is still no substitute for face-to-face communications, today shared computer networks, shared electronic databases, video teleconferencing, and even e-mail, can allow the design team to *virtually* collocate. In some recent ship acquisitions, ad hoc industry teams have been formed, with different and, often, new partners. Team members are usually separated geographically, as well as organizationally, and *electronic* collocation is a given. In such a distributed design environment, communications, database management, and security must receive a high priority in planning, maintenance, and operations. If a key communications system goes down, productivity quickly suffers. Face to face meetings should still occur regularly. The design management plan must ensure that sufficient resources are provided for the tools needed to support the virtual collocated team, and for the necessary travel.

5.5.4 Integrated Design Systems/Modeling and Simulation

The application of computers to the ship design process continues to evolve. In the (not that distant) past, a design site could be recognized by:

- many engineers working with pencils and paper, hand books, mechanical calculators, slide rules, and trig tables, and
- a large number of draftsmen laboring over drawing boards with T-square's, triangles, French curves, battens and batten weights (ducks).

Perhaps the first computer applications used computer programs written to solve discrete, math-intensive problems in order to save labor and achieve more consistently accurate results. This required adapting physics-based models (PBM) to the computer. Languages were rudimentary by today's standards, data was input by punch cards and batch processed on a mainframe in non-real time (often over night), and output was typically tabular numerical data; graphical output lay in the future. As local PCs became available (and later, powerful engineering workstations), turnaround time was reduced. These engineering programs (there are scores in the marine field alone) were developed by engineers (and organizations) to suit their specific needs, often on an ad hoc, stand-alone basis. Accordingly, many different computer languages were used, documentation was often meager, and the various programs could not *talk* to each other. Over time, commercial programs were developed in the U.S. and overseas. This field is described as Computer Aided Engineering (CAE) (see Chapter 13 - Computer Based Tools).

At the total ship level, computer-based ship design synthesis models have been in use for several decades. They permit a large number of concept alternatives to be generated quickly. Such models are only as good as their databases, and thus are not as useful when an entirely new (novel) design is being considered. They provide answers that are relatively correct, which is adequate for making comparIsons.

Soon, the computer also started to be used to generate 2-D lines drawings using commercial software. Even with a skilled practitioner, establishing the initial baseline was relatively slow, but subsequent changes and revisions could be incorporated much more rapidly than in the manual process. The next evolutionary step was to 3-D computer drawings (or solid models). Preparing 3-D drawings by hand required art as well as science. Technology enables the rapid preparation of 3-D computer drawings based on an available 2-D baseline. This field is described as CAD (Computer Aided Design; see Chapter 13 - Computer Based Tools).

In the 1980s, drawings (analog or digital) described the ship's geometry. Interference checking in highly congested areas of the ship was very difficult, labor intensive and time-consuming. Many times problems would not be discovered until ship construction started, resulting in costly and time-consuming rework. Today, highly congested areas of the ship can be modeled in 3-D (solid modeling). This might include piping systems, structures, installed equipment, ventilation ducting, electric power cables, passageways, doors, and ladders. Potential interference problems can readily be identified and resolved.

Independently, shipbuilders (and others) were applying the power of the computer to manufacturing (CAM). Initially this was restricted to NC (numerically controlled) machines that performed very discrete tasks (for example, milling machines). Later, computer lofting was used to dimensionally describe structural plates and shapes and, ultimately, to direct cutting heads and shaping rollers. Eventually, shipyards developed 3-D computer models to aid in *interference checking* between systems competing for space within a compartment. Previously this had been accomplished by overlaying 2-D drawings on a light table. Shipyards procured commercial CAM programs, or developed their own, or created hybrids. There were no industry standards; indeed, the shipyards viewed these programs as proprietary.

Essentially all of the CAE, CAD, and CAM programs discussed above were developed independently, some by Governments (navies) and some by industry. These stand-alone programs solved discrete problems. Standards and interfaces were poorly defined. There was little or no linkage.

What has been described thus far represented at best a federation of a myriad of programs. The next step was to develop a truly *integrated design system* (Figure 5.11).

CAD programs describe the *geometry* of a system or, even the total ship. A natural extension to the use of CAD has been the relatively recent development of 3-D digital product models. **In** addition to providing an accurate geometric description, they also include product characteristics such as mass, material properties, electric power/cooling requirements, and manning requirements.

Originally conceived to facilitate communications between design team members, product models are becoming the primary vehicles for transmitting the ship design description to the shipbuilder. This has the potential to eliminate the need for the shipbuilder to develop its own 3-D model. This reduces time, cost, and the introduction of errors. Issues such as interface standards and protocols must, however, be addressed. **In** addition, upon ship delivery, the *as-built* 3-D product model will provide the basis for configuration control and managing changes throughout the ship's operational life.

CAE programs describe the *behavior* of a system, or even the total ship. A natural extension to the use of numerous CAE codes has been the relatively recent development of dynamic (vice static) physics-based models.

In a recent U.S. Navy design of an amphibious warfare ship, dynamic physics-based modeling was used to quantify the forces placed on the boat crane when handling boats in Sea State 3. (The seakeeping analysis for the selected hull form was imported into the program to provide ship motions). The program was used to evaluate commercial cranes to see if they could satisfy the requirement. Performance parameters were then used to specify system requirements in commercial terms, and eliminate the use of the typical multi-tier military specification. This is an example of the application of an Integrated Design System (IDS) where the geometry model and the engineering analysis models can readily communicate with one another.

When a 3-D product model and physics-based models are married, the result is a *smart product model* (SPM). The SPM can also include bills of material, manufacturing processes, maintenance requirements, and cost analysis tools-the list is endless.When the SPM is combined with state-of-the art visualization and high-speed computers, *simulation based design/virtual prototyping (SBDNP)* becomes possible. As is well known, ships are rarely prototyped because ofthe time and cost involved. There is no *realfty before buy*. As a result, in series production many ships may be under construction before the lead ship delivers. To minimize risk, developmental systems may be tested in land-based test sites or at sea. This, however, is expensive and, for naval ships, occurs late in the ship development cycle.

The ship as a whole is not tested until after delivery. It is only then that the actual performance achieved can be measured against the desired capabilities established many years earlier. At this stage, schedule and cost considerations preclude correcting all but the most severe deficiencies. *SBDNP* offers the opportunity to short circuit this process by the use of virtual ship prototypes in a virtual environment.

In the deck crane example mentioned above, experienced deck seamen were able to *operate* the crane in real time, and provide feedback to the designers. Virtual prototyping has been used to mimic the loading and off-loading of tracked and wheeled vehicles from a sealift ship.

The ultimate goal is to be able to conceive, design, build, and test the ship in a computer long before any manufacturing proceeds.

5.5.5 Risk Analysis

The dictionary defines risk as a chance or possibility of danger, loss, injury, etc. Risk is part of life. It results from the inability to accurately predict the future, and a degree of uncertainty that is significant enough to be noticed. Any key factor that is unknown represents risk. Risk is therefore tied to knowledge or, more accurately, the lack thereof (see Chapter 19 - Reliability-based Structural Design).

The synthesis and analysis of an engineering system often involves the development of a model. Today this frequently means a computer-based model. In fact, however, a model is simply an abstraction of reality, and engineers have always employed them (a sketch of a ship or a system or a mathematic expression or formula is therefore a model). Model uncertainties arise because of simplifying assumptions, simplified methods, and idealized representations of real (physical) behavior and performance.

At the beginning of the design process, knowledge can be categorized three ways:

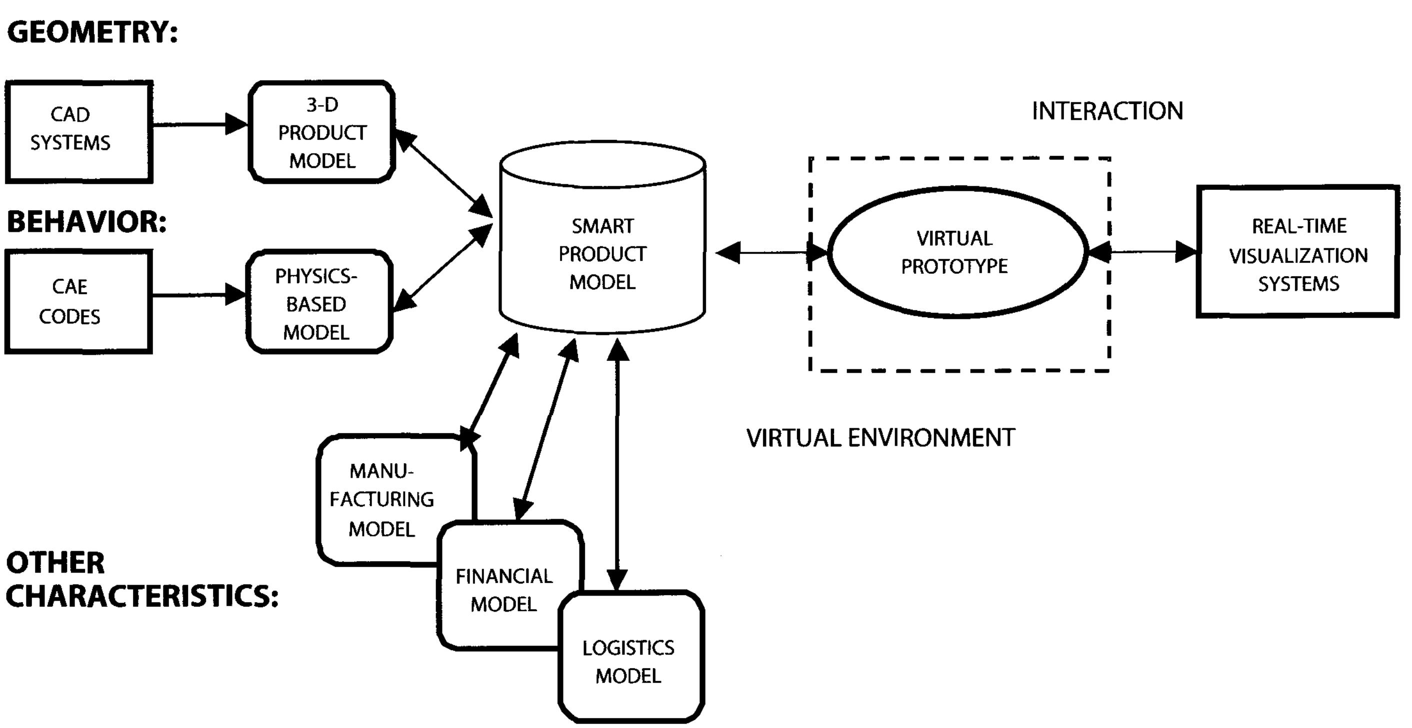

Figure 5.11 Integrated Design System

1. that which is known,
2. that which is unknown, *but* known to be unknown, and
3. that which is unknown, and *not* known to be unknown.

An example of something that is known is the body of knowledge. This might be publicly available or unique to the team (proprietary). There should be no risks associated with applying this knowledge.

In the ship design process, however, not everything can be known at the beginning. During the early concept stages, for example, simplifying assumptions are made based on experience, parametric studies, or databases of similar ships. As the design matures, analysis, detailed engineering, and model tests will confirm (or modify) the earlier assumptions. This is a part of normal design development, and margins may be applied to ensure that the performance envelopes are not violated. Typical margins include speed/power, weight and VCG, but may also include kW and HVAC requirements, and manning (accommodations). It also may be prudent to develop fallback positions. Since the genesis of risk is uncertainty, applying additional engineering resources may be appropriate (for example, apply resources to accelerate model testing, or the development and testing of a new system). As the design matures, the *known unknowns* will move into the *known* category and risks will be reduced.

In ship design development there are also unknown unknowns. By definition, they cannot be quantified, and are difficult to anticipate. History tells us, however, that on a *statistically significant basis* they will arise. Examples include an unanticipated change in shipowner requirements or a new shipowner or major decision maker for government programs, major cost or schedule changes, loss of key design personnel, an energy crisis or labor unrest causing loss of productivity during construction, new national or international regulations, a *technology breakthrough* (or a technology failure), and a major vendor leaving the business or ceasing production of a line of equipment. Another example that falls into the category of an unknown-unknown is human error. Anticipating such risks is obviously quite difficult since it can only be done subjectively, even if by experts.

Design has been defined as the selection and integration of systems and subsystems to meet the requirements and constraints. Risk, whether technical, cost, or schedule, must be of concern to the design team. Every effort must be made to identify risks and work to reduce them during the design and construction process. This activity is termed Risk Analysis. Risk analysis consists of three major components: risk assessment, risk management, and risk communications.

Risk Assessment is the process of deciding how significant a potential hazard is. First, the hazards are identified and qualitatively described. The design engineer has traditionally been primarily concerned with technical risk (performance), but should also be concerned with cost and sch~dule risks since design decisions may influence them. There are also secondary risk areas such as the market place, national and world economic trends, energy crises, availability of labor, legislation, etc. Risks are identified after an analysis of the customer's requirements and constraints, and an assessment of the needed technologies and capabilities.

After the risks are identified, they are prioritized so that management attention and resources can be focused on those risks that are most important. A common approach is to estimate both the likelihood of an event (probability of occurrence) and the associated consequences. The probability of occurrence will range from zero to unity. High probabilities will be assigned, for example, when the required technology is pushing the state of the art and is untested. Conversely, a low probability of occurrence is assigned when using proven technology or off-the-shelf equipment. Next, for each risk the severity of consequence is estimated (severity could also be ranked on a zero to unitary scale). A high number is assigned if the program is threatened (either from a performance, cost, or schedule viewpoint). A low number is assigned when there are fallback positions. When the two numbers are multiplied together, an overall risk ranking is produced.

While is it impossible to avoid value judgments (that is, bias and preconceptions), the assessment should be as objective and consistent as possible.

Commercial software programs are available to assist in these tasks. The more sophisticated might explore the premise that probabilities are not unique but, rather are distributed (a rectangular or triangular function might be assumed, or a bell shaped curve, or a skewed curve). Monte Carlo simulations can be applied in a computer model a large number of times until the pattern becomes evident. These programs are also useful for conducting sensitivity analyses.

Risk Management is the process of selecting alternatives and deciding how to *mitigate* an assessed risk. For purposes of this discussion, the designer is primarily concerned with engineering risks, but risk management involves consideration of a variety of factors including engineering, technology, economics, political, legal, and even cultural considerations. Risk mitigation can be designed to either reduce the probability of occurrence of a risk, or the consequences, or both. After alternative risk mitigation actions have been developed and the cost to execute them estimated, senior managers decide which to implement.

Risk Communications is the process by which information is exchanged about risk. During the course of design development, risks must be tracked and reported. Risk should be an agenda item during all design reviews. Ifthere are a large number of risk areas, periodic risk reviews can be held to ensure that all risks are being managed, that the assessments are current, and that the mitigation plans are achieving their desired results. If new risks are identified, they must be assessed as described previously, and mitigation plans developed.

5.5.6 Decision-making

Decisions must be made at every stage of the design development process in the course of choosing among the technical alternatives that are typically available to meet functional requirements. There are two classes of decisions (14), namely when:

1. technical alternatives are finite and available (as in a catalogue), and
2. alternatives must be synthesized.

Traditionally, it has been assumed for both classes of decisions that the technical requirements are mutually compatible. Thus feasible alternatives can be developed, selection criteria (an objective function) established, the criteria applied and a selection made. No real decision-making is involved. However, when the requirements governing a selection are in conflict, which is often the case in design situations, the designer's priorities will determine the solution. In such cases, the decision-making process is as important as the facts upon which the decision is based. Multiple CriteriaDecision Making (MCDM) methods (15) are designed to address this kind of problem. The MCDM approach clarifies the trade-offs between objectives and permits them to be manipulated; better decisions are the result.

There is a large array of methods that deal with multiple criteria problems. Four Multi-Attribute Decision Making (MADM) models are described, evaluated and demonstrated in reference 15. They are:

- Weighted Sum
- Hierarchical Weighted Sum
- Analytical Hierarchy Process (AHP)
- Multi-Attribute Utility (MAU) Analysis.

All of these MADM methods simplify and clarify the design decision-making process by transforming multi-dimensional decision problems to a single criterion, a Figure of Merit (FOM), which is used to indicate the overall design *goodness* for each alternative. All the methods allow subjective assessments to be translated into quantitative values for evaluation purposes. The quantification process does not make the decision process objective, but it does allow the design team to explore the effects of their choices of attributes, weights, etc. The latter three methods all represent improvements over the traditional weighted sum technique at the expense of added complexity. Including risk and uncertainty in the evaluation is desirable; however, doing so adds further complexity. The reference presents a quantitative method for performing cost-effectiveness trade-offs using the DDG 51 as a ship design example. The importance of evaluating cost and effectiveness separately in performing such trade-offs is emphasized. They are independent qualities. If the cost and effectiveness FOMs for each alternative are plotted, the design team may be fortunate enough to find that the optimum solutions plot along a rough curve. In this case, the *best* of the optimum solutions will generally lie at the knee of the curve.

Quality Function Deployment (QFD) is a management tool developed by a Japanese shipbuilder in the late sixties to support the design process for large ships. QFD is a method for structured product planning and development. It translates customer requirements into requirements for the product development team. QFD has also been defined as *a system for designing a product or service based on customer demands and involving all members of the producer or supplier organization.* QFD is a planning and decision making tool; it is a good example of concurrent development. QFD enables the development team to identify the customer's wants and needs and then to systematically evaluate each potential product attribute in terms of its contribution to satisfying the needs. The process involves constructing one or more matrices or *quality tables;* see Figure 5.12, from reference 16. Matrix 1 in the figure is termed the *House of Quality* (HOQ) due to its shape.

The first step in the process is to identify the customer's requirements such as wants and needs, likes and dislikes, termed the WHATS. The customer is defined as any user of the design. Thus there is typically more than one customer, for example, the shipowner, the ship operators (future crew), the shipbuilders, the future ship maintainers, etc. The needs and desires of these *customers* are identified, based on consensus, and then prioritized (weighted). Many representatives of each customer group might be polled to assist in this step.

The next step is to develop the HaWS, that is, the design requirements (technical measures of performance) that, if met, will produce satisfied customers. There must be at least one HOW for each WHAT and there may be more. Also, each HOW will typically influence more than one WHAT. The HaWS and WHATS are then correlated by means of a 2-D matrix, the WHATS along the left side and the HaWS along the top. This matrix, the HOQ, is an effective aid in untangling the complex web of relationships between the WHATS and the HaWS. The HaWS associ-

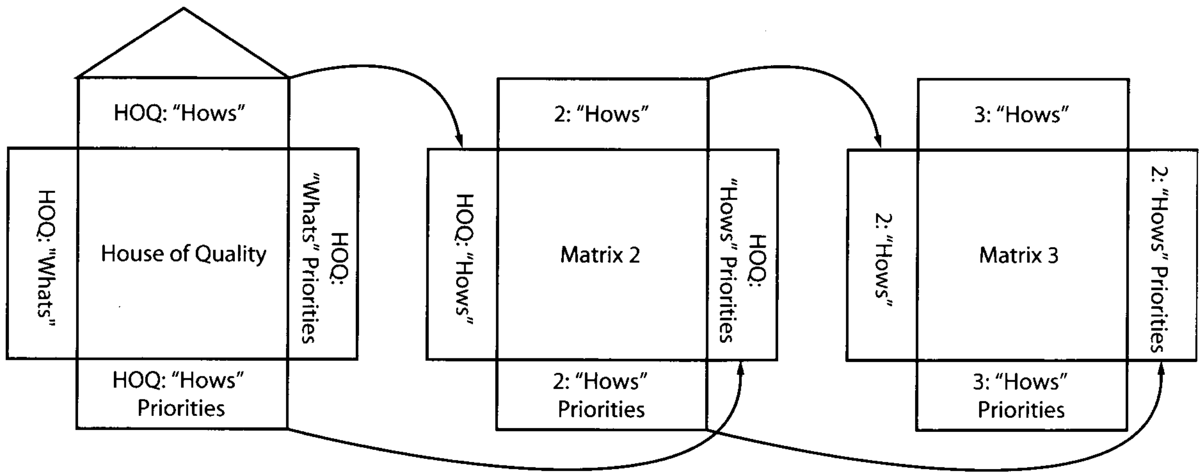

Figure 5.12 QFD Matrix Chain

ated with each WHAT are noted in the appropriate boxes of the matrix and the strength of each association is estimated. By this means, the relative benefits of each HOW can be expressed numerically, that is, the HOWS can be prioritized or weighted. In addition, the HOWS can be correlated with one another and the strengths of the relationships noted. This is done in the *attic* of the HOQ.

Strong positive correlations indicate synergy and possibly duplication. Negative correlations indicate conflicts and opportunities for trade-offs. Ultimately, the HOWS are quantified by "how much," that is, specific performance objectives expressed in measurable terms. In more sophisticated analyses, the cost of each HOW is estimated (design development, construction, and TOC). This can be combined with the weights (relative importance) ofthe WHATS, and the development team can see what the cost vs. performance actually is.

Typically, the HOWS in the HOQ (Matrix 1) are not sufficiently detailed to be used directly in product design. The matrix chain depicted in Figure 5.12 is provides the required definition. In each successive matrix, the WHATS are the HOWS from the preceding matrix and the HOWS represent a more specific, detailed decomposition of the performance measures, attributes and characteristics of the product being developed.

In each successive matrix, correlations can be identified and the strengths of these correlations can be judged. By this multi-step process, the customers' desires can be linked to system features and the relative importance of various system features can be assessed. This knowledge can be used to influence the allocation of design resources and the numerous trade-off decisions that must be made during design development. The QFD approach and philosophy can be applied to numerous other aspects ofthe product development process. The brief outline above is intended only to give the reader an indication of the basic QFD goals and approach. In addition to providing design guidance, QFD shines at facilitating self-interviews within the design team, consensus building and improving communications among the stakeholders in a large project.

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Chapter 6

Engineering Economics

Harry Benford

6.1 NOMENCLATURE

6.1.1 Economic Terms

A	uniform annual amounts, annual returns, annuities
A	annual cash flow after tax
A_B	annual payment on a loan (capital plus interest)
AAB	average annual benefit
AABI	average annual benefit index
AAC	average annual cost
ACR	annual charter rate
a	cost of the first unit of a series
BCP	benefit cost ratio
CA	compound amount factor
CC	capitalized cost
CR	capital recovery factor
CR'	capital recovery factor after tax
CV$	constant-value dollars
CVA	annual amounts in constant-value dollars
D	annual depreciation allocation
d	general inflation rate per year, also days in transit
DCF	discounted cash flow rate of return
ECT	economic cost of transport
F	a single future amount
FV$	face-value dollars
FVA	fixed annual amounts in face-value dollars
g	a gradient
R	period of a bank loan
I_B	uniform annual interest payments on a loan
i	interest rate (usually per year)
i'	interest rate after tax
i_B	bank interest rate per year
L	resale or disposal value
LCC	life cycle cost
M	million, also compounding periods per year
M&R	maintenance and repair
N	a number of years in the future, life of an investment, also number of identical units
NPV	net present value
NPVI	net present value index
OR	overhead cost per year
P	principal, initial investment, present worth, present value
P_B	amount of a loan
P_R	residual debt
PBP	payback period
PW	present worth, present value, also present worth factor (single payment)
Q	tax life, depreciation period
r	discount rate applied to constant-value dollars
r_1	effective annual interest rate
r_M	nominal annual interest rate with non-annual compounding
RFR	required freight rate
SCA	series compound amount factor
SF	sinking fund factor
SPW	series present worth factor
SYD	sum of the year's digits (depreciation)
t	corporate tax rate
v	unit value of cargo
x	a maverick inflation rate
Y	uniform annual operating costs
Y_D	daily operating costs annualized

Y_V voyage costs per year
$\underline{Y}$ cumulative average cost for a series of sister ships
Z a special non-annual expense, also years remaining in a cash flow
difference between two uniform annual amounts

6.1.2 Ship Terms

B ship's beam
CN cubic number
D depth
DWT deadweight
L length
V_K speed in knots
WE empty weight, lightship

6.2 INTRODUCTION

6.2.1 Engineering Economics Defined

Typically one talks to scientists in terms of physics and mathematics, *but to business people in tenns of economics.*

This chapter presents an introduction to engineering economICS.

What is meant by the term *economics?* The usual understanding is that the subject deals with the wise use of scarce resources: human power (whether mental, physical, or both); materials; available physical facilities, such as machinery; and money to spend (commonly called *capital).*

Thus it can be seen that *Economics* is not just about money. Money must, nevertheless, be brought into the picture. Why? Simply because in deciding how best to use all those scarce resources (in their disparate forms) it is necessary to find some common unit of measurement for weighing the importance of each. Money is that common unit in whatever monetary unit is appropriate to the preparer of the analysis. The subject of finance deals with raising and repaying capital and it is briefly considered in Section 6.6.

Finally, then, *engineering economics* can be defined as the art and science of making design decisions that meet society's needs while making the best possible use of scarce resources.

6.2.2 Engineering Economics as a Tool

Engineering economics provide a means of making rational decisions. However, remember that decisions are between *alternative choices.* If there are no alternatives, no decision is required. If your client gives you detailed requirements, there is no need to waste time in weighing the relative merits of other solutions. Conversely, if there is a choice between two or more alternatives, concentrate attention on their'differences. Those factors that are the same can more or le~s be ignored. Take, for example the case of choosing between two different kinds of machinery for a ship. One type may require a larger engine crew than the other. If that is the case, careful thought should be given to engine crew wages, but little time should be wasted on those of the deck crew.

To summarize, engineering success depends largely on economic success. Every design decision should consider how that decision would affect the overall economics of the unit in question. Moreover, history shows that many successful engineers eventually move in to positions where business decisions are made, and some advance to the top of the managerial ladder. As they move up that ladder a knowledge of economics becomes ever more important.

6.2.3 Systems

When making a decision one should be sure that in benefiting one component, others are not overly degraded. To avoid such sub-optimization the overall economics of the entire system should be analyzed.

An important step here is to use care in defining the system that is to be considered. The boundaries should be drawn in such a way that any given decision will not cause an adverse impact on components outside the system.

The following examples illustrate this principle. Each case involves the transport of iron ore.

Case 1: The size of the ship is fixed by the locks of a canal. The aim of the study is to choose the best kind of propulsion plant. No matter what plant is chosen, the cargo handling costs and terminal costs will be the same. In this case the system can be defined as the ship itself. Optimize the ship and ignore the terminal.

Case 2: The ore is to be moved in pellet form. It will be loaded and unloaded at proposed deep offshore terminals. There are no locks to be transited and no real limits on ship size. There are appreciable benefits in making the ship as big as possible. Those benefits, however, will be offset by added costs of providing the correspondingly larger terminals. There will be no effect on the inland legs of the movement. The system can now be defined as terminal gate to terminal gate.

Case 3: The question is whether to move the ore in its raw state, in pellet form, or as a slurry.

Now the system must be expanded to include not only the complete source-to-destination transport, but also the processing equipment and operation at each end.

6.2.4 Systems Analysis

Systems analysis is a methodical approach to decision making involving these distinct steps:

- a clear definition of the system, and its objective stated in functional terms. For example: move 500 000 tons of coal each year from Newport News to Yokohama,
- a clear understanding of the constraints on the operation. For example: flag of registry, labor union agreements, loading and unloading facilities, port and canal limits,
- a clear definition of the economic measure of merit to be used in choosing among alternative proposals,
- a menu of all conceivable, but technically feasible, strategies for achieving the objective in the face of the constraints,
- *estimated* quantitative value of the measure of merit likely to be achieved by each of those strategies, and
- a summary of additional, intangible factors that should be considered before making the decision.

In applying these steps the following should be kept in mind:

- the constraints observed in second step may be considered as subject to relaxation if good enough reason can be found,
- there is no universally agreed-upon measure of merit,
- generating the menu of alternative strategies is the truly creative part of this procedure. No two engineers are likely to produce the same selection,
- note that *strategies* are considered rather than simply *designs.* This is because not only the hardware must be considered, but also the method of operation,
- the word *estimated* is stressed in the fifth step because the figures one derives are based on best estimates about future costs and conditions,
- if the aim is to maximize human satisfaction, one must recognize that some important considerations cannot readily be expressed in dollar terms. Pride in owning a good-looking ship surely counts for something, as one example, and
- finally, because of the above intangible factors, the alternative that promises the best value of the measure of merit will not necessarily be the best choice. It is probable that the key decisions will be made by the responsible business manager rather than the engineer. The engineer's task, then, is to reduce the list of alternatives to a modest menu of choices each of which promises close-to-maximum value of the measure of merit. To this should be appended a few sentences discussing the various intangible considerations that come to mind. The manager is then equipped with a selection from which to choose and a rational basis on which to make the decision.

6.2.5 More Real-life Complications

In Subsection 6.2.4 it was stressed that economic studies should concentrate on the differences between alternatives. A second basic principle is that the *differences* in cash flowing in or out of the enterprise *as a result of the decision* must be predicted. A corollary that follows is that the past can be ignored, because the past is common to all alternatives.

Related to the above is the rule that lost opportunity costs must be given as much emphasis as real costs. Passing up an opportunity to gain a thousand dollars is every bit as bad as making a decision that leads to a thousand-dollar loss. This is one of the major points of difference between engineers and accountants. Lost opportunity costs never show up in the books, and so are ignored by accountants.

Another difference to keep in mind is that accountants focus on past results whereas engineers look ahead. Other differences will be discussed in later sections.

6.3 THE TIME-VALUE OF MONEY AND CASH FLOW

6.3.1 The Human Logic

The subject of time-value of money is not confined to inflation or deflation. Primarily it is concerned with the natural human instinct for finding more pleasure from money in hand today than the firm expectation of acquiring an exactly equal amount, corrected for inflation, at some time in the future.

For example which would a person rather have today: a \$1000 bill or a legal document entitling a withdrawal of \$1000, plus increment for any inflation, from a bank a year from now? Most people would select the first alternative.

Carrying this analysis a bit further. Would a person rather have \$1000 now or the firm promise of a million dollars a year from now? Again most people would surely have enough patience to wait for the million dollars. So what specific amount to be received a year from now would leave a person hesitant to decide? If that figure happens to be \$1200, then that individual's personal time value of money amounts to twenty percent annual interest. *Interest,* is in effect, rent paid for the use of money. It is commonly expressed as a percentage of the initial capital, with rent falling due at the end of every year.

6.3.2 The Financial Logic

So far the discussion has concerned the logic of interest in purely human, psychological terms. One can also think about it in cold-blooded financial terms. Let us consider the case of a person who inherits a million dollars. One possible investment might be an apartment house that costs exactly a million dollars and promises clear annual profits of $50 000, amounting to, five percent of the investment. If some reliable bank offers six percent annual interest, that might be considered a superior investment.

6.3.3 Relative Merits of the Two Approaches

If one recognizes that the ultimate aim of engineering is to provide products that satisfy a social need, then it can be argued that the psychological rationale discussed in Subsection 6.3.1 is really more important than the unemotional tools of financial analysis discussed in Sub-section 6.3.2. But, the psychological approach is weak in that any individual's personal time-value of money will tend to change from day to day or even during the day depending on the fluctuating state of various influences. Nevertheless, despite their weaknesses, subjective feelings will dominate in personal decision-making whether by ordinary individuals or by wealthy entrepreneurs dealing with their own cash.

Corporations, on the other hand, must be more coldly analytical and base most decisions on strictly financial matters. There are, it is true, psychological influences at play because the overall satisfaction of the shareholders must be considered when deciding on dividends. In short, then, both elements have their roles in weighing the time-value of money.

6.3.4 Three Ways of Thinking about Interest

The time-value of money can be thought about in three distinct settings:

1. *Contracted interest* is the kind with which most people are most familiar. Savings deposits in banks, loans from banks, mortgages, and bonds all carry mutually agreed-upon interest rates.
2. *Implied interest* is appropriately considered when funds are tied up to no advantage. If a person hides money under the mattress, that action is in effect costing at least as much as the interest that could have been earned by putting the money in a savings account in a bank. (This is an example of a lost opportunity cost.) and
3. *Returned interest* is a measure of gain, if any, from risk capital invested in an enterprise. This is called by various names including *internally generated interest, interest rate of return,* or simply *yield.* It is one good measure of profitability, expressing the benefits of an investment as equivalent to returns from a bank at that derived rate of interest. Most nations impose a tax on business incomes, so one must differentiate between returp.s before and after tax.

In all of the above, the important thing to remember is to weigh the time value of money by the exact same mathematical expressions in all three cases. Another important rule in engineering economics:

In deciding between alternatives, one must consider for each not only how much money flows in or out, but also when.

It is important to clearly understand that throughout this chapter the discussion is about *compound,* as distinct from *simple,* interest. In the former, the interest payments are due at the end of each period. If they are left unpaid, they will b~ added to the debt. Thus the debt would increase exponentially over time. With simple interest, no payments become due until the debt is paid. That is less logical and the plan is seldom used.

6.3.5 Cash Flow Diagrams

Cash flow diagrams are an important convention that engineering economists use in communicating their ideas. This refers to simple schematics showing how much money is being spent or earned year-by-year. In them, the horizontal scale represents future time, generally divided into years. The vertical scale shows annual amounts of cash flowing in (upward pointing arrows) or out (downward pointing arrows).

Part of the convention is that work is simplified by assuming that all the cash flow occurs on the last day of each year. Whatever inaccuracy this throws into the calculations tends to warp results to pretty much the same degree for all alternatives being considered, and so should have little effect on the decision.

Figure 6.1 shows a typical irregular cash flow pattern. Other common patterns are shown in Figure 6.2.

The single-letter abbreviations used in the diagrams are standard notation used by most engineering economists and defined in Section 6.1.

The diagrams are drawn from the perspective of a lender or an investor. A borrower, on the other hand, would picture the arrows reversed, but the method of analysis would be exactly the same.

Ships have long economic lives, usually at least twenty years. It is therefore justifiable to treat cash flows on an annual basis. For shorter-term studies, briefer time periods can be used, perhaps months. The basic principles and mathematics remain the same. See the end of the section for more details.

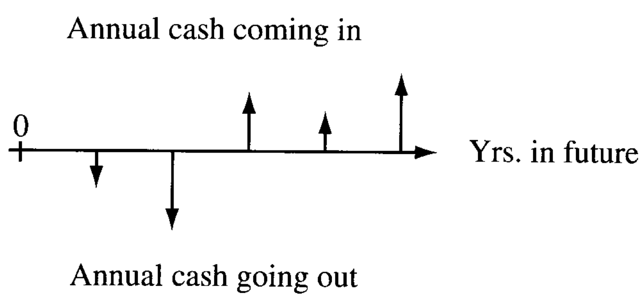
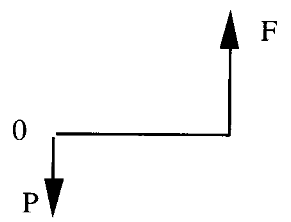
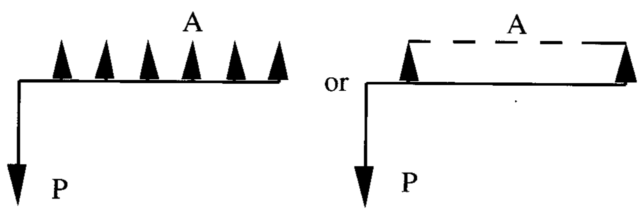


Figure 6.1



Single investment, single pay back



Single investment, uniform annual returns

Figure 6.2

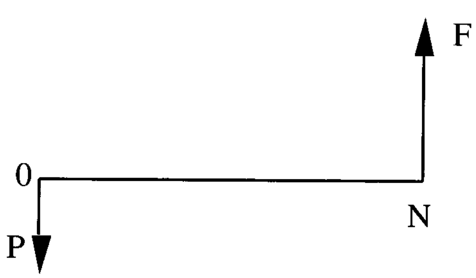


Figure 6.3

6.3.6 Six Basic Interest Relationships

All of the 6 basic interest relationships apply to three simple cash flow patterns. These are as follows:

6.3.6.1 Single-investment, Single-payment

First, is the single-investment, single-payment pattern shown in Figure 6.3.

Knowing the initial amount, P, and wanting to find the future amount, F, multiply P by what is called the *single payment compound amount factor* (usually shortened to simply *compound amount factor*). If the time period is but a single year, the future amount, F, would equal the initial amount, P, plus the interest due, which would be i × P. In short

$$F = P + iP = P(1 + i)$$

If the time period, N, is some integer greater than one, then the debt would have compounded as a function of that number of years, leading to the general expression

$$F = P(1 + i)^N$$

The factor (1 + i) is the compound amount factor. It is abbreviated CA and, when associated with a given interest rate and number of years, the combination is indicated by the convention: (CA – i – N). Thus the single compound amount factor for 12 percent interest and 15 years would be shown as (CA – 12% – 15).

This new concept, the *single present worth factor,* is often shortened to *present worth factor.* This being the case, the abbreviation P can now be taken to mean *present worth* or *present value.* The terms are used interchangeably.

Reversing the process, if it is desired to obtain a single future amount the equivalent initial value can be found by multiplying the desired amount by the reciprocal of the compound amount factor

$$P = F / (1 + i)^N$$

Two examples will illustrate these concepts. First, suppose a person has $100 spare cash and decides to put it into a savings deposit with a bank. The bank offers 7% annual interest. If the $100 is left in the bank for two years, how much could be withdrawn at the end of that period?

This calls for the use of compound amount factor

$$\begin{aligned} F &= P(CA - 7\% - 2) \\ &= \$100\,(1 + i)^2 \\ &= \$100\,(1.07)^2 \end{aligned}$$

To derive the numerical value of the compound amount factor interest tables such as 6.1 (A) can be used. It is the reciprocal of the present worth factor shown in the table. In this case the PW factor is 0.8734, so

$$F = \$100 \times 1 / 0.873 = \$64.50$$

Simply stated, if $100 were put in the bank today and allowed to compound at 7% per year, that would allow a withdrawal of $64.50 two years hence. It could be said that, given a time-value of money equivalent to 7% interest, $100 today is equal in desirability to $64.50 two years from now. Conversely, then, the firm promise of $64.50 two years from

TABLE 6.1 (A) Interest Factors—Single Present Worth Factors (PW)

N i = *1%*		*2%*	*3%*	*4%*	*5%*	*6%*	*7%*	*10%*	*12%*	*15%*	*20%*
1	.9901	.9804	.9709	.9615	.9524	.9434	.9346	.9091	.8929	.8696	.8333
2	.9803	.9612	.9426	.9246	.9070	.8900	.8734	.8264	.7972	.7561	.6944
3	.9706	.9423	.9151	.8890	.8638	.8396	.8163	.7513	.7118	.6575	.5787
4	.9610	.9238	.8885	.8548	.8227	.7921	.7629	.6830	.6355	.5718	.4823
5	.9515	.9057	.8626	.8219	.7835	.7473	.7130	.6209	.5674	.4972	.4019
10	.9053	.8203	.7441	.6756	.6139	.5584	.5083	.3855	.3220	.2472	.1615
15	.8613	.7430	.6419	.5553	.4810	.4173	.3624	.2394	.1827	.1229	.0649
20	.8195	.6730	.5537	.4564	.3769	.3118	.2584	.1486	.1037	.0611	.0261
25	.7798	.6095	.4776	.3751	.2953	.2330	.1842	.0923	.0588	.0304	.0105
50	.6080	.3715	.2281	.1407	.0872	.0543	.0339	.0085	.0035	.0009	.0001

Note: Single Compound Amount Factors (CA) are the reciprocals

TABLE 6.1 (B) Interest Factors—Capital Recovery Factors (CR)

N i = *1%*		*2%*	*3%*	*4%*	*5%*	*6%*	*7%*	*10%*	*12%*	*15%*	*20%*
1	1.0100	1.0200	1.0300	1.0400	1.0500	1.0600	1.0700	1.1000	1.1200	1.1500	1.2000
2	.5076	.5155	.5226	.5305	.5376	.5455	.5529	.5760	.5917	.6150	.6545
3	.3401	.3466	.3534	.3604	.3671	.3741	.3811	.4021	.4164	.4380	.4747
4	.2564	.2625	.2691	.2755	.2820	.2886	.2952	.3155	.3292	.3503	.3863
5	.2062	.2121	.2183	.2246	.2309	.2374	.2439	.2638	.2774	.2983	.3344
10	.1056	.1113	.1172	.1233	.1295	.1359	.1424	.1627	.1770	.1993	.2385
15	.0721	.0778	.0838	.0899	.0963	.1030	.1098	.1315	.1468	.1710	.2139
20	.0554	.0612	.0672	.0736	.0802	.0872	.0944	.1175	.1339	.1598	.2054
25	.0454	.0512	.0574	.0640	.0710	.0782	.0858	.1102	.1275	.1547	.2021
50	.0255	.0318	.0389	.0465	.0548	.0634	.0725	.1009	.1204	.1501	.2000

Note: Series Present Worth Factors (SPW) are the reciprocals

TABLE 6.1 (C) Interest Factors—Sinking Fund Factors (SF)

N i = *1%*		*2%*	*3%*	*4%*	*5%*	*6%*	*7%*	*10%*	*12%*	*15%*	*20%*
1	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
2	.4975	.4950	.4926	.4902	.4878	.4854	.4831	.4762	.4717	.4651	.4545
3	.3300	.3268	.3235	.3203	.3172	.3141	.3111	.3021	.2963	.2880	.2747
4	.2463	.2426	.2390	.2355	.2320	.2286	.2252	.2155	.2092	.2003	.1863
5	.1960	.1922	.1884	.1846	.1810	.1774	.1739	.1638	.1574	.1483	.1344
10	.0956	.0913	.0872	.0833	.0795	.0759	.0724	.0627	.0570	.0493	.0385
15	.0621	.0578	.0538	.0499	.0463	.0430	.0398	.0315	.0268	.0210	.0139
20	.0454	.0412	.0372	.0336	.0302	.0272	.0244	.0175	.0139	.0098	.0054
25	.0354	.0312	.0274	.0240	.0210	.0182	.0158	.0102	.0075	.0047	.0021
50	.0155	.0118	.0089	.0066	.0048	.0034	.0025	.0009	.0004	.0001	.0000

Note: Series Compound Amount Factors are the reciprocals now has a present worth of \$100. This mental exercise of converting future amounts back into present worths is a valuable tool in economic analysis, and one that will be exploited frequently in this chapter.

Second, assume a given individual has a personal time value of money amounting to 12% interest. What should he be willing to pay for a financial document that promises to pay \$1000 five years from now? Applying the present worth factor (PW)

$$\begin{aligned} P &= F(PW - 12\% - 5) \\ &= \$1000(0.5674) \\ &= \$567.40 \end{aligned}$$

Now suppose instead of 12% interest, the decision is made to use 20% because that is what is promised by another investment opportunity. This leads to

$$\begin{aligned} P &= \$1000(PW - 20\% - 5) \\ &= \$1000(0.4019) \\ &= \$401.90 \end{aligned}$$

Comparing this new present value of \$401.90 against the previously found \$567.40, one can see that the higher interest rate has reduced the present worth of the future \$1000. In short, ascribing high numbers to the time-value of money, diminishes the importance of future benefits. This fact is important to keep in mind.

Throughout the rest of this chapter, to save space, the numerical values of the various interest factors will not be shown. It will be assumed that they are built into one's computer, or that one knows how to derive them from a table.

6.3.6.2 Single Investment, Uniform Annual Payments

The next set of interest relationships apply to a single initial amount, P, balanced against uniform annual amounts, A, as shown in Figure 6.4.

If the uniform annual amounts, A, can be predicted and one wants to find the present worth of them, P, one can use this expression (the proof of which can be found in standard texts)

$$P = [(1+i)^N - 1] / i(1+i)^N$$

The component $[(1+i)^N - 1] / i(1+i)^N$ is called the *series present worth factor*. When associated with a given interest rate and number of years it is designated thus: (SPW – i – N). For example, if the interest rate is 12% and the number of equal payments is 15: (SPW – 12% – 15).

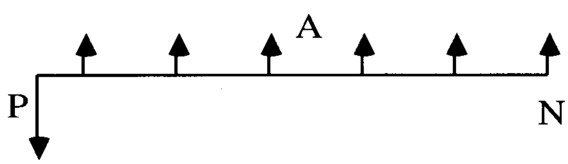


Figure 6.4

This relationship is useful for situations in which the size of future uniform annual returns from an investment can be predicted and one wants to find out how much one can afford to put into that investment.

It should be noted that, unless otherwise stated, it should always be assumed that annual amounts and annual interest rates are used.

An example involving the present worth of a future uniform annual cash flow is as follows:

A company that commonly earns 10% interest on its investments has a chance to buy an existing ship with a remaining life of 5 years and estimated annual clear profits of \$750 000. What is the maximum price the company should offer for the ship?

The decision maker should use the series present worth factor (SPW) to convert an expected annual cash flow of \$750 000 for 5 years into an equivalent single amount today

$$P = \$750\,000(SPW - 10\% - 5) = \$2\,843\,000$$

To be realistic, it would be better form to present the above as \$2.843 million.

Again reversing the approach, suppose the initial amount, P, is known, and it is desired to find the uniform annual amounts of equal present worth. This is the common situation in which one borrows money from a bank in order to buy an automobile and must make uniform periodic repayments that incorporate both return of the initial loan and interest on the residual debt. In that sort of loan the payments usually fall due every month, but the principle is still the same as with annual payments. The relationship is now

$$A = Pi(1 + i)^N / [\, i(1 + i)^N - 1]$$

The component $i(1 + i)^N / [\, i(1 + i)^N - 1]$ is called the *capital recovery factor* and is abbreviated CR. When associated with a given interest rate per compounding period, i, and number of compounding periods, N, we show it as (CR – i – N).

As another example:

A proposed fishing boat is estimated to cost \$2 500 000. The owner has a time value of money as 12% annual interest. The life of the boat is expected to be 20 years. In order to justify the investment, what is the minimum annual cash flow the boat should be able to generate? Now the owner can use the capital recovery factor (CR) to convert the first cost of \$2 500 000 to a uniform annual cash flow of equal desirability (A)

$$\begin{aligned} A &= P(CR - 12\% - 20) \\ &= \$2\,500\,000\,(CR - 12\% - 20) \\ &= \$334\,700 \end{aligned}$$

6.3.6.3 Uniform annual deposits, single withdrawal

Our third pair of interest relationships apply to the cash flow pattern shown in Figure 6.5

A strange quirk about this pattern is that at the end of the final year we have arrows pointing in opposite directions. This is done to simplify the calculations. In truth, of course, in real life the net amount paid would not be F, but F minus A. Another possibility is that within a business setting the annual amounts would actually comprise continual cash deposits during the year. One may nevertheless assume single year-end amounts.

If the uniform annual amounts (A) are known, and it is desired to find the equivalent single future amount (F) that can be withdrawn, multiply A by the series compound amount factor (SCA)

$$(SCA - i - N) = [(1 + i)^N - 1]/i$$

For example, if $100 is deposited each year into a bank account paying 7% annual interest, how much should the depositor be able to withdraw at the end 10 years?

$$F = \$100(SCA - 7\% - 10) = \$1381.64$$

If it is desired to reverse the procedure and find out how much must be deposited each year in order to build up some specific future amount (F), one would multiply that future amount by what is called the sinking fund factor (SF), which would of course be the reciprocal of the series compound amount factor

$$(SF - i - N) = i / [(1 + i)^N - 1]$$

Say it is desired to build up an amount of $15,000 five years from now so a sailboat may be bought. The decision is made to place annual amounts in a bank offering 8% interest compounded annually. How much must be deposited each year?

$$A = \$15\,000(SF - 8\% - 5) = \$2556.85$$

6.3.7 Non-uniform Cash Flows

Suppose one predicts cash flows of $100 in year 1, $50 in year 2, nothing in year 3, a loss of $100 in year 4, and a gain of $200 in year 5 (the end of the project's economic life). If the interest rate is 10%, what is the present value of this predicted cash flow? The cash flow diagram is shown in Figure 6.6.

The approach to such a problem is simple. Each individual amount is merely discounted back to year zero using 10% interest and appropriate values of N.

For $100 one year, hence

$$P = \$100(PW - 10\% - 1) = \$91$$

For $50 two years, hence

$$P = \$50(PW - 10\% - 2) = \$41$$

For nothing 3 years, hence

$$P = 0$$

For a loss of $100 4 years, hence

$$P = (\$100)(PW - 10\% - 4) = (\$68)$$

For $200 five years, hence

$$P = \$200(PW - 10\% - 5) = \$124$$

Present worth = net sum of the above = $188

As may be noted in the above, negative cash flows are placed in parentheses.

The analysis should be laid out in a neat table exactly as an accountant would do it, as shown in Table 6.II.

6.3.8 Gradient Series

There may be cases where it can be predicted that future cash flows will be increasing by a fixed amount (abbreviated *g*) each year.

The present worth of such a cash flow could be found with a year-by-year analysis just as shown in Figure 6.7.

A more sophisticated (and usually easier) way would be to first find the equivalent uniform annual amount (A) by means of the following formula

$$A = A_1 + g / i - Ng(SF - i - N) / i$$

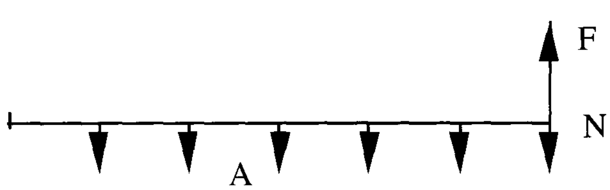


Figure 6.5

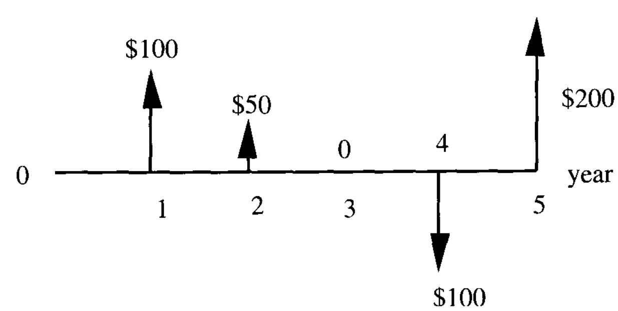


Figure 6.6

The present worth could then be found using the appropriate series present worth factor

$$P = A(SPW - i - N)$$

If the pattern shows a uniform *downward* slope, then the equivalent uniform annual amount would be

$$A = A_1 - g / i + Ng(SF - i - N) / i$$

For example, find the present worth of a cash flow that starts at \$1000 the first year and then increases \$200 per year for the next 4 years (i.e., g = \$200 and N = 5). Use 15% interest.

To solve this, first find the equivalent uniform annual amount, A

$$A = \$1000 + \$200 / 15\% - 5 \times \$200\ (SF - i - N) / 15\% = \$1334$$

Then convert that to its present worth

$$P = \$1344(SPW - 15\% - 5) = \$4505$$

and that is the answer.

6.3.9 Stepped Patterns

Another common variation involves cash flows that remain uniform for some number of years (or other compounding periods) but then suddenly increase or decrease. In real life this might come about because of the peculiarities of the tax laws, as one example. Assume a simple case in which there is no income for the first 5 years and then uniform annual amounts of \$175 are expected through the 20th year. The object is to find the present worth based on 10% interest.

One way to solve this problem would be to analyze the cash flow year-by-year in a table, but there are easier ways. One would be to use the standard series present worth factor to find the equivalent value at the year just before the cash flow started, for example, year 5, and then to discount that to year zero using the single present worth factor

$$P \text{ at year } 5 = \$175(SPW - 10\% - 15) = \$1331$$
$$P \text{ at year } 0 \text{ (today)} = \$1331\ (PW - 10\% - 5) = \$826$$

Another logical technique would be to compute the present worth of \$175 per year as though the cash flow occurred throughout the full 20 years, and then subtract the present worth of the first 5 years, in which it did not occur.

$$P = \$175(SPW - 10\% - 20) - \$175(SPW - 10\% - 5) = \$1490 - \$663 = \$827$$

This is in reasonable agreement with the \$826 found above.

As shown later, the second method is often neater and easier to use.

Another example involves two levels of uniform annual cash flow. In this case one can predict an annual cash flow of \$140 for each of the first 5 years of a project and \$100 for years 6 through 10, after which the project will be closed down with no residual value. The intent is to apply an interest rate of 10% to find the present value of the predicted cash flow. Figure 6.8 shows the cash flow diagram.

Start by finding the present worth of the \$100 cash flow over the complete 10 years and then adding the present worth of the difference between \$140 and \$100 (i.e., Δ = \$40) over 5 years.

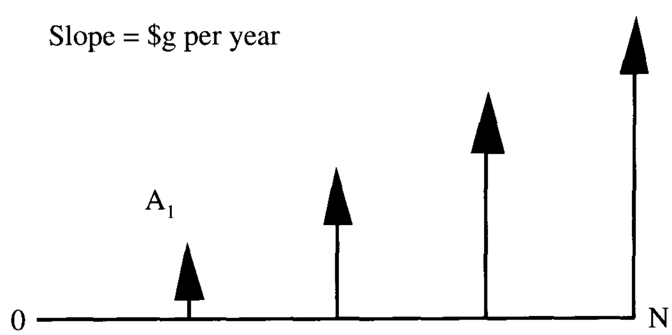


Figure 6.7

TABLE 6.II

N = year	*Amount*	*(PW – 10% – N)*	*Product*
1	\$100	0.909	\$91
2	\$50	0.826	\$41
3	0	0.751	0
4	(\$100)	0.683	(\$68)
5	\$200	0.621	\$124
Total present worth:			**\$188**

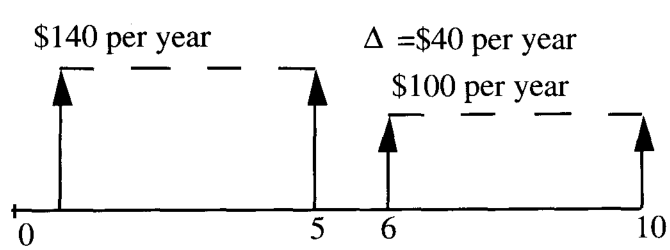


Figure 6.8

$$
\begin{aligned}
P &= \$100(SPW - 10\% - 10) + \$40(SPW - 10\% - 5)\\
&= \$614 + \$152\\
&= \$766
\end{aligned}
$$

The same logic can be used in situations where the uniform annual amounts increase, rather than decrease at some point. Repeating the previous illustration, but reversing the cash flow pattern, can show this. Now one may assume uniform annual amounts of $100 for each of the first 5 years, and $140 for each of the final 5 years as shown in Figure 6.9.

Again, start by finding the present worth of the second series ($140 per year) and then *subtracting* for the increment (~= $40)

$$
\begin{aligned}
P &= \$140(SPW - 10\% - 10) - \$40(SPW - 10\% - 5)\\
&= \$860 - \$152\\
&= \$708
\end{aligned}
$$

This second outcome, $708, compares with the $766 found in the previous study. The same total amount of money came in, but the present value in the first case would be greater because more of the money came in during the early years. The quick buck is the good buck.

The analytical technique developed above can be applied to cash flows that involve more then the two levels of income shown. The same technique can also be applied to negative cash flows or combinations of positive and negative flows.

6.3.10 Periodic Discrepancies

Over the life of a ship, typically 20 years, there will usually be periodic special expenses for planned maintenance work. These may occur perhaps every four years. The projected operating cash flow pattern might then consist of uniform annual expenditures (which we shall abbreviate X) plus special increments, Z, every fourth year, as shown in Figure 6.10.

How can such a pattern be converted into equivalent uniform annual amounts? The unsophisticated method is to discount each of the special expenses (Z) back to the present, summing those amounts and then multiplying that sum by the capital recovery factor to find the equivalent uniform annual amount. The sophisticated method is to convert each Z amount into its equivalent uniform annual amount by multiplying it by the sinking fund factor appropriate to the number of years between the occurrences of the special expenses.

The equivalent uniform annual operating cost, Y, would then become

$$Y = X + Z(SF - i - 4)$$

However, it is unlikely that maintenance will be performed during the final year of a ship's life, so this approach is not precise as it does not take that into consideration. Eliminating that final Z expense would produce a cash flow such as shown in Figure 6.11.

This will require that the Y value shown above be reduced by a uniform annual amount equivalent to the Z spread over the entire 20-year life. That uniform decrement will amount to Z times the sinking fund factor based on the full 20 years. The equation now becomes

$$
\begin{aligned}
&Y = X + Z(SF - i - 4) - Z(SF - i - 20)\\
\text{or, } &Y = X + Z\{(SF - i - 4) - (SF - i - 20)\}
\end{aligned}
$$

To illustrate this with a simple example, suppose the ship's life is projected to be 25 years. An interest rate of 12% is specified. The uniform annual costs of operation are expected to be $800 000. Every fifth year there will be special survey expenses of $1.5 million. This special cost will be waived during the final year of the ship's life. Find the equivalent uniform annual expense. The cash flow pattern is shown in Figure 6.12.

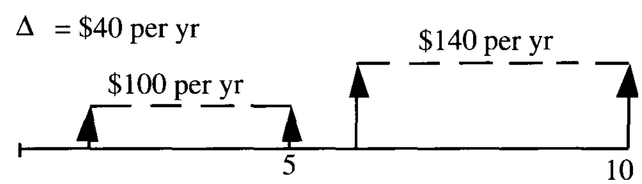


Figure 6.9

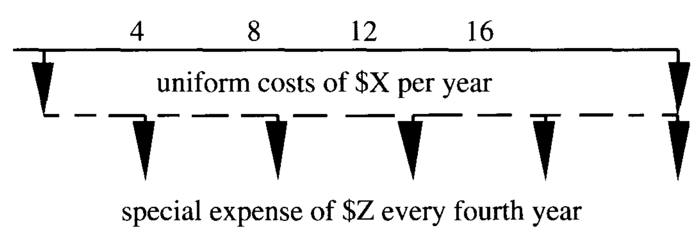


Figure 6.10

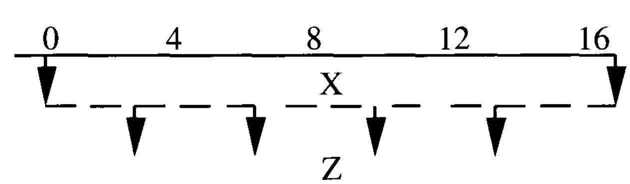


Figure 6.11

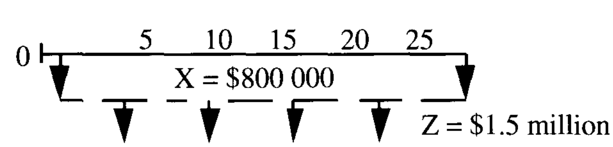


Figure 6.12

$y = X + Z\{(SF - 12\% - 5) - (SF - 12\% - 25)\}$
$Y = \$800\ 000 + \$1.5\text{million}\ \{O.1574 - 0.0075\}$
$Y = \$800\ 000 + \$225\ 000$
$Y = \$1\ 025\ 000$

6.3.11 Inflation

This section explains how to analyze monetary inflation, particularly how it may influence decision-making in ship design. It will be shown that in most cases the effects will be trivial. There may, however, be special situations in which inflation should not be overlooked.

If one can assume that a shipowner is free to raise freight rates commensurate with any future inflation in operating costs, then all financial and economic factors will float upward on the same uniform tide. If that occurs, the optimum ship based on no inflation will also be the optimum ship in which inflation is taken into account. Inflation need be of concern only when some major economic factors are expected to change appreciably faster or slower than the general trend.

Money does one no good until it is spent, and if its purchasing power is rubbery, one should admit as much. If a good meal in a restaurant costs $15 today and is expected to cost $30 in five years, one would be foolish to ignore that threat. To clarify thinking in all this, one must train oneself to think in terms of constant-value dollars. In short, do not try to analyze long-term cash flows without first adjusting each year's figure according to its purchasing power relative to some convenient base year.

The constant value dollars are the ones corrected for inflation and are the ones for which an engineer should develop an affinity.

The question then arises, how best to convert misleading Future Value (FV$) into reliable Current Value (CV$)? There are two alternative methods. Both are based on the same principles and, if correctly carried out, should produce the same final outcome and resulting design decision. One-way is to prepare a year-by-year table in which all cash flows are entered in CV$. The analyst is then in a position to apply standard interest relationships to find the present value or equivalent uniform annual cost of this CV$ cash flow in the usual way.

The other approach, as might be guessed, is to start with FV$ and apply a discount rate that has built into it adjustments for both inflation and time-value of money. This method can be handled by simple algebraic procedures and does not require the time consuming, error-prone, year-by-year tabular approach described previously. It allows one to find the present worth (corrected for inflation) of a future cash flow that is subject to predictably changing dollar values.

The task is to derive the value of i for any given set of assumptions as to the rate of inflation and time-value of money. Remember that i incorporates both time-value of money and; inflation. One way is to start with the simple case in whicb a given category of cost is floating up right along with the general inflation rate, d. That being the case, although it appears to be increasing (in FV$), it is really holding steady in real purchasing power. That is, it is always the same in CV$, so we can ignore inflation and say

$$l=r$$

Next consider the case in which one category of cash remains fixed in face value dollars during a period of general inflation. A fixed charter fee might lead to such an arrangement. Some tax calculations also involve fixed annual amounts. In any given year

$$FVA = A_0$$

Correcting for inflation

$$CVA = FVA / (1 + d)^N = A_0 / (1 + d)^N$$

And

$$P = CVA/(1 + r)^N = A_0 / (1 + r)^N(1 + d)^N$$

That is, double discounting is employed, once for the time-value of money, and again for the declining real value of the dollar. In short, where costs remain fixed in FV$ one may use

$$i = (1 + r)(1 + d) - 1$$

Finally, consider the case of a cost factor that changes at an annual rate, x, that differs from general inflation. In face-value terms

$$FVA = A_0(1 + x)$$

Correcting for inflation

$$CVA = FVA / (1 + d)^N = A_0(1 + x)^N / (1 + d)^N$$

and, converting to present worth

$$P = CVA / (1 + r)^N = A_0(1 + x)^N / (1 + d)^N(1 + r)^N$$

So, where maverick costs are concerned

$$i = [(1 + r)(1 + d) / (1 + x)] - 1$$

This final expression may, in extreme cases, produce a negative interest rate (equivalent to paying the bank to guard cash). This will lead to a present worth exceeding the future amount. This is perfectly reasonable and a calculator will handle it automatically.

Table 6.III summarizes the interest rates that help us find present values in CV$ in times of inflation.

The following example illustrates the concepts explained above. Over a four-year period there are predicted three concurrent cash flows as follows.

Wages: Fixed by contract at $100 000 per year (FV$)

Fuel: Starting at $120 000 per year and increasing at 16% per year

All other costs: Starting at $80 000 per year and rising with inflation.

General inflation is expected to amount to 12% per year and the time-value of money is set at 9% per year. Table 6.IV shows how this problem can be handled in tabular form. An important but less-than-obvious point is that the initial amounts are taken at *year zero, not year one.*

Turning now to the algebraic approach, these values are first noted

Time value of money: r = 9%
General rate of inflation: d = 12%
Rate of inflation for fuel: x_{fuel} = 16%

Then, analyzing each cost component in turn shows:

Wages: These are fixed in face value terms, so

$$i = (1 + r)(1 + d) - 1 = (1.09)(1.12) - 1 = 22.08\%$$

To find the present worth in CV$, apply the series present worth factor for 22.08 percent interest and four years:

PW in CV$ = $100000 (SPW - 22.08% - 4) = $249 000

Fuel: This inflates at its own rate, so:

$$i = [(1 + r)(1 + d) / (1 + x_{fuel})] - 1$$
$$i = [(1.09)(1.12) / (1.16)] - 1 = 5.24\%$$

PW in CV$ = $120 000 (SPW - 5.241 %-4)
= $423 000

TABLE 6.11I Interest Rates Applicable During Periods of Inflation

Cash Flow characteristics	*Interest Rate to be Applied to Initial AnnualAmount*
Floats up with general inflation	l=r
Fixed in FV umits	i = (1 + r)(l + d) - 1
Changes at annual rate, x, other than general inflation rate, d	i = [(1 = r)(l + d) / (1 + x)] - 1

Other: These costs float up with general inflation, so :

l=r
i=9%
PW in CV$ = $80000 (SPW - 9% - 4)
= $259 000

Total: The total present worth in CV$ will equal the sum of the three components derived above:

Total PW = ($249 + $423 + $259) x 10_3 = $931 000

6.3.12 Non-annual Compounding

In most ship design studies engineers are in the habit of assuming annual compounding when weighing the time-value of money. There may be instances, however, when other compounding periods should be recognized. As the reader may recall, the standard interest formulas introduced at the start of this chapter are applicable to any combination of compounding periods and interest rate *per compounding period.* Take, for example the standard single payment compound amount factor and apply it to a $10 000 debt with 12% interest compounded annually over a 20-year period. What would be the total debt, F, at the end of that period?

F=P(CA-i-N)
= $10 OOO(CA- 12% - 20)
= $96 450 (rounded)

TABLE 6.1V Handling Inflation with the Tabular Approach

a *year (N)*	b *Wages*	c *Fuel*	d *Other*	e *Total Costs*	f *(PW - 9% -N)*	g *PW*
1	89	124	*80*	293	*0.9174*	269
2	80	129	80	289	0.8417	243
3	71	133	80	284	0.7722	219
4	64	138	80	282	0.7084	200
Total present worth:						931

Notes: See text for details. Cash amounts shown in the table are in thousands of CV$. Notes below pertain to the corresponding columns.

b. In CV$, wages, ArJ(1 + d)N = S 100 000 / (1.12)N
c. In CV$, fuel cost = $120 000 (1.16)N / (l.12)N =Ao(1 + X)N/ (1 + d)N = $120 000 / (1.036)N
d. In CV$; other costs remain fixed at $80 000
e. Column e = sum of columns b, c and d
f. (PW - 9% - N) = 1 / (1.09)N
g. PW = column e mulitplied by column f

Next, suppose the terms of the loan called for the same 12% interest, but compounded quarterly. Now the number of compounding periods will quadruple to 80, and our interest rate per compounding period will be cut to a quarter, or 3%.

F = $10 OOO(CA - 3% - 80) = $106 400 (rounded),

which is more than 10% greater than the figure based on annual compounding.

Clearly, when changing the frequency of compounding one also changes the weight given to the time-value of money. This is common sense; the more often repayments fall due, the more desirable is the arrangement to the lender, and the less desirable to the debtor. In order to make a valid comparison between debts involving differing compounding periods, we need an algebraic tool that will assign to each repayment plan a measure that is independent of frequency of compounding.

The usual approach to this operation is based on what is generally called the *effective interest rate*, abbreviated t. This is an artificial interest rate per annum that ascribes the same time-value to money as some nominal annual rate, rw with M compounding periods per annum.

For example, suppose one loan plan is based on quarterly compounding at one interest rate, and another is based on monthly compounding at a somewhat lower rate. It is not possible to tell by looking at the numbers, which is more desirable. If both nominal annual rates are converted to their corresponding effective rates, however, those values will tell which is the better deal. The question then arises, how does one convert from a nominal annual rate, r_M, to effective rate, r_1? The simple key is

$$r_1 = (1 + r_M / M)^M - 1$$

For the derivation of this equation, see any standard engineering economy reference.

To illustrate, consider the following example. Suppose banker A offers to lend money at 12% compounded semi-annually. Banker B offers 6.5% compounded monthly. B's nominal rate is lower, but the compounding is more frequent, so one cannot readily tell which is the better offer. What is needed is to convert each nominal rate to its corresponding effective rate.

For Banker A

$$r_M = 12\% \text{ and } M = 2$$

so

$$r_M / M = 6\% = 0.06$$

and

$$r_1 = (1.06)^2 - 1 = 12.36\%$$

For Banker B

$$r_M = 6.5\% \text{ and } M = 12,$$

so

$$r_M / M = 0.96\% = 0.0096$$

and

$$r_1 = (1.0096)^{12} - 1 = 12.13\%$$

Comparing the two effective rates, it can be concluded that Banker B offers a slightly better deal; that is, a lower effective interest rate.

The equation for effective rate, r_1, can be rewritten to provide this expression for deriving a nominal rate per compounding period from any given effective rate

$$r_M / M = (1 + r_1)^{1/M} - 1$$

One important rule to keep in mind: *Never use a nominal annual rate all by itself. Always convert it into its corresponding rate per compounding period.*

6.4 TAXES AND DEPRECIATION

6.4.1 Perspective

Today, very few maritime nations impose an annual tax on corporate earnings of shipping companies. The U.S. is still one that does. Therefore, naval architects involved in the design of a commercial ship for U.S. shipowners and flag should have at least a rudimentary idea about the applicable tax structure. In many cases a proper recognition of the tax law will have a major impact on design decisions. In other cases, as shown later, taxes can be ignored. In any event, a naval architect should understand enough about the subject to discuss it intelligently with business managers.

Tax laws are written by politicians who are swayed by pressures coming from many directions and are changed over time. As a result tax laws are almost always complex, and continually changing. Thus, most large companies employ experts whose careers are devoted to understanding the tax laws and finding ways to minimize their impact. No attempt is made here to explain all the complexity of current tax laws; but some simple tax concepts are outlined and their effects on cash flow explained.

6.4.2 Tax Shields

In most traditional maritime nations, in contradistinction to so-called open-registry nations, corporate tax rates run around 40 to 50 percent of the before-tax cash flow *minus certain tax shields.* Principal among these are an annual allocation for depreciation and any interest paid to a bank or other source of income involving fixed payments. The impact of bank loans is discussed in Section 6.5. For now it is assumed that the owner is able to pay for the ship with his own capital. This is called an all-equity investment.

6.4.3 Depreciation

Depreciation is, in a way, a legal fiction with roots in long-established accounting practices. When a company makes a major investment it exchanges a large amount of cash for a physical asset of equal value. In its annual report it takes credit for that asset and shows no sudden drop in company net worth. Over the years, however, as the asset becomes less valuable for various reasons, its contribution to the company's worth declines; that is, it *depreciates.*

Depreciation is a legal fiction to the extent that the tax laws treat it as an expense in a time period other than when the money was actually spent. Remember the rule: accurate economic assessment recognizes not only how much cash flows in or out, but also *when.* Another fictitious element is found in the fact that few nations allow owners to recognize inflation when figuring depreciation.

In summary of what has been covered so far, it has been shown that the tax collector's target is not the company's actual annual cash flow (income minus costs), but a distorted version of that cash flow. Depreciation allocations recognize capital investments, not in the year they are made, but rather distributed over a period of years. The principal objective of this chapter, then, is to explain some of the major schemes for assigning annual depreciation allocations and their effects on tax liabilities.

6.4.4 Straight-line Depreciation

In its simplest form, the ship (or other facility) is assumed to lose the same amount of value every year until the end of its economic life. This is called *straight-line depreciation.* It is found by dividing the depreciable value by the number of years of life

$$D = (P - L) / N$$

In most cases one is justified in ignoring the disposal value. It is typically less than 5% of the initial investment; it is hard to predict; and, being many years off, has little impact on overall economics. Thus, for design studies, straight-line depreciation is usually taken as

$$D = P / N$$

6.4.5 Cash Flows Before and After Tax

The bar diagram in Figure 6.13 shows how annual revenues are treated when figuring corporate income taxes. It's assumed here that all factors remain constant over the N years of the project's economic life. (This is what economists call a heroic assumption, but it is frequently good enough for design studies.)

The bar diagram shows that the annual cash flow after tax (A′) is related to the cash flow before tax (A) by this simple expression

$$A' = A(1 - t) + t\,P / N$$

or, turning it around

$$A = (A' - tP / N) / (1 - t)$$

An important thing to note is that all of our rational measures of merit are based on after-tax cash flows, not profits. *In short, one should not use profits to measure profitability, but use cash flows instead.* Profits are misleading because they are polluted with depreciation, an expense that is misallocated in time.

6.4.6 Fast Write-off

In the preceding section the assumption was made that the ship's tax life coincided with its economic life. This is not always the case because owners are sometimes permitted to base depreciation on a shorter period. It is called *fast write-off.* It is advantageous to the investor. This is so because it provides a more favorable after-tax cash flow pattern. Over the life of the ship the same total taxes must be paid, but their worst impact is delayed. Remember, money today is always preferable to money tomorrow.

Some nations allow shipowners freedom to depreciate their ships as fast as they like. In that setting the owner can make the depreciation allocation equal to the cash flow before tax. That will reduce the tax base to zero, and no taxes

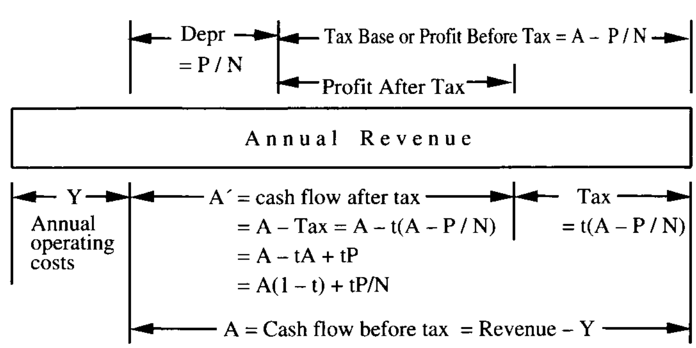


Figure 6.13

need be paid during the early years of the ship's life. After that, of course, the depreciation tax shield will be gone, and higher taxes will ensue. Again, however, the total tax bill over the ship's life will remain the same, unless they sell it before the expected life.

More typically, the owner will not be given a free hand in depreciating the ship. Rather, the tax life, that is, depreciation period, will be set at some period appreciably shorter than the expected economic life. This will result in cash flow projections that feature uniform annual amounts with a step down after the depreciable life is reached. Here is how to handle such a situation.

First, give separate attention to two distinct time periods. The first of these comprises the years during which depreciation allowances are in effect, the final such year being identified as Q.

The second time period follows Q and extends to the final year of the ship's economic life, designated with the letter N. Assuming straight-line depreciation, the cash flows before (A) and after *(X)* tax will be related as shown in Figure 6.14.

Now, recalling how stepped cash flows were handled in Subsection 10.3.9, the present worth of the above can be found as follows:

$$PW = A(1 - t)(SPW - i' - N) + (tP / Q)(SPW - i' - N)$$

This concept is clarified with this numerical example. Assume that an owner expects a ship to have an economic life of 20 years, with negligible disposal value. The tax depreciation period is 12 years. The tax rate is 40%. The initial cost is $24 million. The annual revenues are $3.2 million and annual operating costs are $800,000. Find the after-tax cash flows during years 1-12 and 13-20, then find the present worth ofthe cash flows using 12% interest. Figure 6.15 is a schematic of the cash distributions.

$$A = Rev - Y = \$3.2M - \$0.8M = \$2.4M$$

During the initial 12 years

$$\begin{aligned} A' &= A(1 - t) + tP / Q \\ &= \$\,2.4M(1 - 0.40) + 0.40 \times \$24 / 12 \\ &= \$2.24M \end{aligned}$$

After that, with no tax shield

$$\begin{aligned} A' &= A(1 - t) \\ &= \$\,2.4M(1 - 0.40) \\ &= \$1.44M \end{aligned}$$

The cash flow pattern is shown in Figure 6.16.

The present worth of the cash flow is

$$\begin{aligned} PW &= \$1.44M(SPW - 12\% - 20) + \$0.80M(SPW - 12\% - 12) \\ &= \$10.76M + \$4.96M \\ &= \$15.72M. \end{aligned}$$

Consider next the case where fast write-off is not allowed, i.e., where the tax life and economic life are the same: N years. Given that assumption, the after-tax cash flow, (A′), would be equal to

$$\begin{aligned} A' &= A(1 - t) + tP / N \\ &= \$\,2.4M(1 - 0.40) + 0.40 \times \$24M / 20 \\ &= \$1.92M \end{aligned}$$

so PW = $1.92M(SPW – 12% – 20) = $14.34M, which compares with $15.72M attained with fast write-off, as shown above, nearly a 10% advantage in favor of fast write-off.

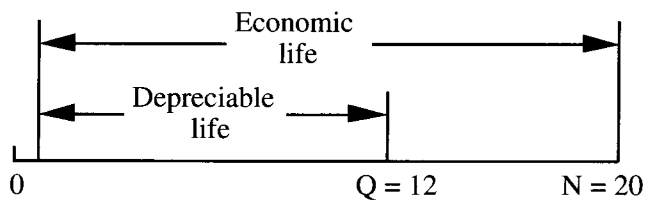


Figure 6.15

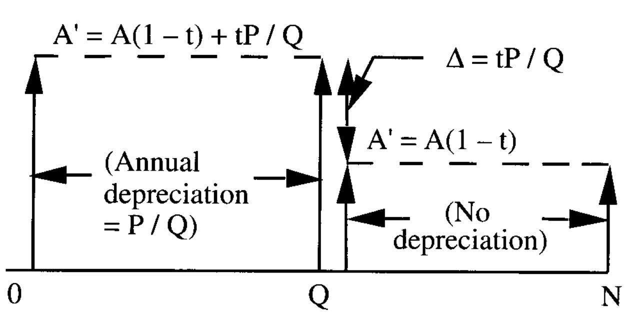


Figure 6.14

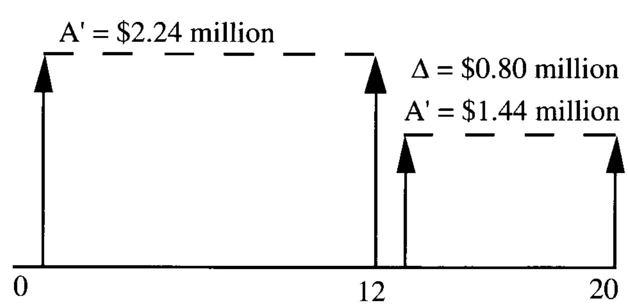


Figure 6.16

Next, one may compare the total tax amounts paid over the life of the ship in each case. With fast write-off the annual tax during the first 12 years would amount to

$$\begin{aligned}\text{Tax} &= t(A - P / Q)\\ &= 0.40(\$2.4M - \$24M / 12\\ &= \$0.16M \text{ per year}\end{aligned}$$

The annual tax during the final 8 years would amount to

$$t(A) = 0.40(\$2.40M) = \$0.96M \text{ per year}$$

The total tax over the 20-year life would be

$$\begin{aligned}\text{Total tax} &= 12\ (\$0.16M) + 8(\$0.96M)\\ &= \$1.92M + \$7.68M = \$9.60M\end{aligned}$$

Without fast write-off, the annual tax during each of the 20 years would be

$$\begin{aligned}\text{Tax} &= t(A - P / N)\\ &= 0.40(\$2.4M - \$24M / 20\\ &= \$0.48M \text{ per year}\end{aligned}$$

The total tax over 20 years would be

$$\text{Total tax} = 20(\$0.48M) = \$9.60M$$

which is the same as with a fast write-off.

The two outcomes, being the same, show that fast write-off does not reduce the tax burden; it merely gives it a less onerous distribution.

6.4.7 Variable Tax Rates

In some nations the tax laws assign one tax rate against taxable income that is turned over to the stockholders in the form of dividends, and a much higher rate against income that the corporation retains (probably in order to expand operations or simply overcome inflation). There is logic in assigning a lower rate against dividends. The government will get its due from the individual income taxes paid by the shareholders. If faced with a dual tax rate setting, it is necessary to ask the shipowner how the company's profits are usually split. Alternatively, assume a 50/50 distribution, leading to an average tax rate applied to the entire taxable amount.

6.4.8 Accelerated Depreciation

Some tax laws recognize that straight-line depreciation is based on an unrealistic assessment of actual resale values of physical assets. This leads to various depreciation schemes that feature a large allocation during the first year of the asset's life and diminishing allocations thereafter. These declining amounts may continue over the entire economic life, or they may lead to complete write-off in some shorter period. One may thus find accelerated depreciation combined with fast write-off. In any event, the total taxes over the asset's life will once more be the same. The primary advantage of such schemes is to offer the enterprise a more favorable earlier distribution of after-tax cash flows.

6.4.9 Some Other Complications

Among other entangling vines in the jungle of taxation is something called the *investment tax credit.* When a government finds the economy slowing, it will want to encourage business managers to spur the economy through new capital investments. The obvious way to do this would be to lower the corporate tax rate. Political leaders may lack the courage to do that, so they look for less visible ways. One such way is the investment tax credit. This allows the organization to reduce its first year's tax on a new project by some modest fraction of the initial investment. This tax reduction in no way reduces the depreciation allocations and gives business managers added confidence that they will be able to get their money back in a hurry.

How are the depreciation calculations handled when the system under analysis includes components with differing depreciable lives? An example would be a new containerized cargo transport system. There one might find investments in real estate (infinite life), ships (20-year life), cranes 05-year life), and buildings (50-year life). The answer is clear: Each such component must be analyzed separately. The principle is simple and so are the calculations; they just look complicated when taken in total.

When dealing with shipowners naval architects will likely have to talk to accountants who know all the tax rules and want to apply them to the design analysis. Naval architects must of course pay attention to what these people have to say. But they must also realize that they are usually safe in applying massive amounts of simplifying assumptions, at least in the preliminary design stages.

It should be known that some managers use the simplest sort of analysis in choosing projects and in deciding whether or not to go ahead with them. This is so even though they intend to use every possible tax-reducing trick if the project does indeed come to fruition. This suggests the wisdom of using simple methods, for example, straight-line depreciation, in the early design stages when dozens or hundreds of alternatives are under consideration, but then, having narrowed the choice down to half a dozen alternatives, letting the accountants adjust the chosen few to satisfy their needs.

Starting with gross simplifications enables looking ahead to the effect of the more elaborate tax schemes by recognizing that their net effect is to produce some modest increase in present values of future incomes. This may be taken into account by assuming a slightly lower tax rate. Alternatively, future cash flows can be discounted with a slightly lower interest rate.

6.5 LEVERAGE

6.5.1 Perspective

This subchapter examines various ways in which a shipowner may go into debt in order to expand the scope of operations. It is noted that the interest payments incurred may reduce the tax base and so they must be recognized in assessing after-tax cash flows.

Increasingly complicated loan arrangements are considered. There are times when a naval architect will want to apply simple schemes. There will be times when he will want to apply complex schemes. In general, in the preliminary design stages, when dozens or hundreds of alternatives are under consideration, one should be satisfied to use the simplest schemes. At the other end of the scale, when the choice has been narrowed down to half a dozen, the naval architect, the client, or the business manager, can apply many more realistic assumptions if considered necessary.

In general, the more realistic (complex) assumptions will slightly reduce the impact of the income tax. In the early design stages, when assuming simple loan plans, the naval architect may recognize this effect by adding a small increment to the actual tax rate or to the interest rate. The same thought applies to assumptions regarding tax depreciation plans. By using such adjustments, the optimum design as indicated by the simple assumptions will closely approach the optimum as indicated by the more realistic and elaborate assumptions.

Many, if not most, business managers have ambitions beyond the reach of their equity capital. This leads them to *leverage up* their operation by obtaining a loan from a bank. The same is true of individuals who want to own a yacht. It is also often true of governments who sell bonds so as to finance a share of current expenditures. In nearly every case the lender requires repayment of the loan within a given time and at a given interest rate. Typically, the repayments are made in periodic bits and pieces comprising both interest and some reduction in the debt itself. In short, the periodic payments are determined by multiplying the amount of the loan (abbreviated PB) by the capital recovery factor appropriate to the loan period (abbreviated H) and the agreed-upon interest rate (i_B). The typical repayment period is monthly, but for ship design studies one may generally assume annual payments (abbreviated A_B). In short

$$A_B = P_B(CR - i_B - H)$$

As an alternative to applying to a bank, managers may choose to raise capital by selling bonds. As far as one need be concerned here, the effect is the same: the debt must be repaid at some agreed-upon rate of interest.

Section 6.4 explains how depreciation plans affect the corporate income tax. In the United States, at least at the time of this writing, the interest paid to the bank or bondholder is treated as an operating expense and so it, too, reduces the tax.

Bank loans are popular with managers because that source of capital usually implies a lower interest rate than would be demanded by owners of common stock. But, as noted in Subsection 6.7.6, increasing reliance on bank loans carries increasing risk.

6.5.2 Cash Flows Before and After Tax

The bar diagram shown in Figure 6.18 is like the one shown in Figure 6.15 except for the complication of a bank loan. The bank loan period is now assumed to be the same as the ship's economic life (H = N). Straight-line depreciation is also assumed, with depreciation period equal to economic life (Q = N). A final assumption is that the before-tax cash flow (A) remains constant. For many design studies these assumptions are reasonable. A subsequent section treats cases where N, Q, and H all differ.

In analyzing the cash flow distribution shown in Figure 6.18 one more simplifying assumption is used, which involves substituting a uniform annual value of the interest payments (abbreviated I_B) for the actual, ever-diminishing values. Figure 6.17 shows the real distribution between principal and interest as well as the simplification

Shown in Figure 6.18 is the distribution of the annual revenue when both bank loans and straight-line depreciation are involved.

An examination of the diagram leads to this expression relating cash flows before and after tax

$$\begin{aligned} A' &= A - Tax = A - t(A - I_B - P / N) \\ &= A - tA + tI_B + tP / N \\ &= A(1 - t) + tI_B + tP / N \end{aligned}$$

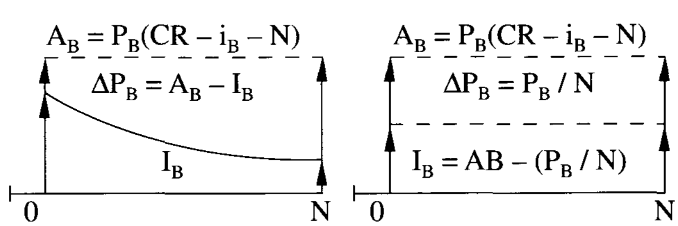


Figure 6.17

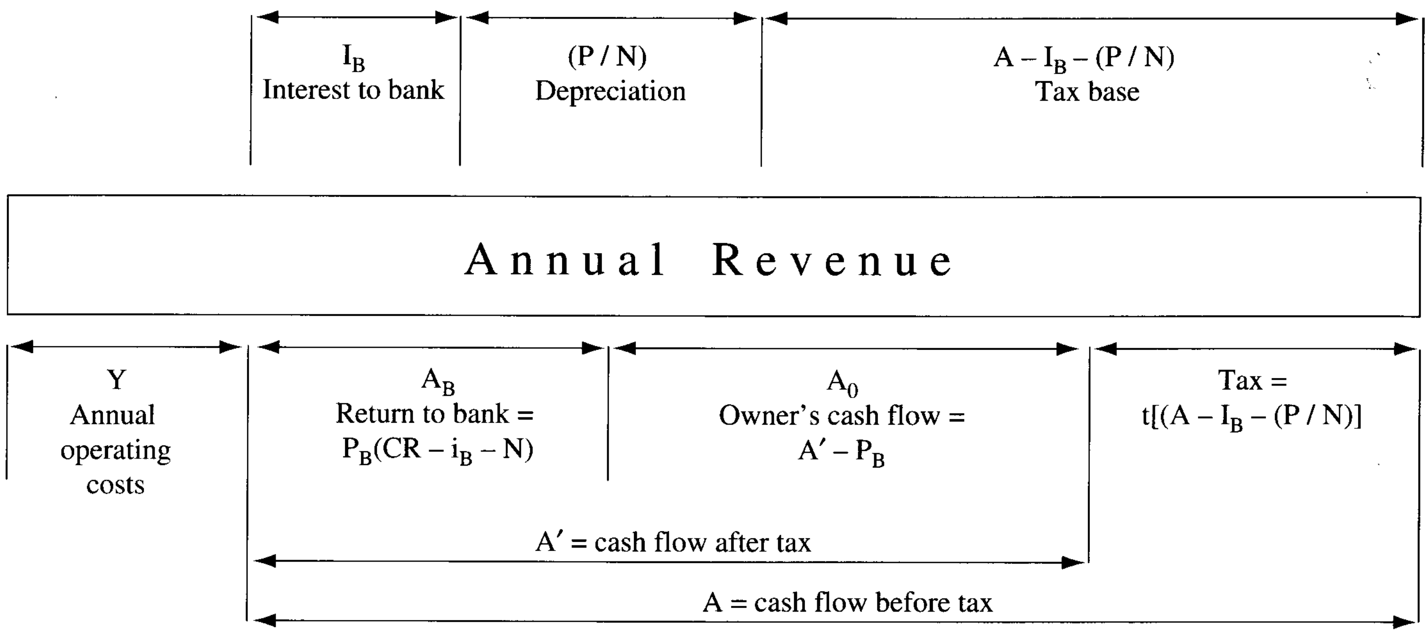


Figure 6.18

Further, the residual annual return to the owner, A_0, will be

$$A_0 = A' - A_B$$

where

$$A_B = P_B(CR - I_B - N)$$

Consider the following example:

Assume a ship that cost \$75 million has an expected economic life of 25 years. The owner uses \$25 million equity capital and the rest comes from a bank loan payable over the 25-year life at 9% annual interest. The ship is expected to earn annual revenues of \$8.25 million against operating costs of \$1.25 million. Assume a tax rate of 45% and straight-line depreciation. Find these four annual cash flows: 1. to owner, 2. to bank, 3. before tax, and 4. after tax.

The first step in solving this problem will be to subtract the owner's equity from the total cost of the ship; that will tell how much must be borrowed from the bank

$$P_B = P - P_0 = \$75M - \$25M = \$50M$$

The annual payment owed the bank is

$$\begin{aligned} A_B &= P_B(CR - I_B - N) \\ &= \$50M(CR - 9\% - 25) \\ &= \$5M \text{ (rounded)} \end{aligned}$$

which is the answer to part 2.

Then, the approximate value of the annual interest payment will be:

$$\begin{aligned} I_B &= A_B - P_B / N \\ &= \$5M - \$50M / 25 \\ &= \$5M - \$2M = \$3M \end{aligned}$$

Next, one needs to find the annual cash flow before tax

$$\begin{aligned} A &= \text{revenue} - \text{operating costs} \\ &= \$8.25M - \$1.25M \\ &= \$7.00M \end{aligned}$$

which is the answer to part 3.

Now one is ready to convert to cash flow after tax

$$\begin{aligned} A' &= A(1 - t) + tI_B + tP / N \\ &= \$7M(1 - 0.45) + 0.45 \text{ x } \$3M + 0.45 \times \$75 / 25 \\ &= \$3.85M + \$1.39M + \$1.35M \\ &= \$6.6M \end{aligned}$$

which is the answer to part 4.

The analysis found the annual payment to the bank as the first step in finding $I_B = \$5M$.

Finally, the owner's after-tax cash flow will be

$$A_0 = A' - A_B = \$6.6M - \$5M = \$1.6M$$

which is the answer to part 1.

6.5.3 Differing Time Periods

To this point it has been assumed that the period of the bank loan and the tax depreciation period both coincided with the economic life of the ship. Next it is appropriate to analyze cash flows before and after tax when those periods are all different. Initially it will be assumed that the loan period, H, is shorter than the depreciation period, Q, which in turn is shorter than the economic life, N. The cash flow diagram would then contain three segments as shown in Figure 6.19.

During Period A the cash flows before and after tax would be as developed in the earlier part of this section except that care must be taken to identify the differing time periods: H, Q, and N.

$$A = A(1 - t) + tIs + tP / Q$$

During Period B the interest payments would no longer be a factor, so the only tax shield would be the depreciation allocation

$$A = A(1 - t) + tP / Q$$

During Period C there would be no tax shields at all, so

$$A = A(1 - t)$$

Putting these individual cash flow back together leads to Figure 6.20.

Applying the techniques in Section 6.3, we can find the present worth of this cash flow as follows

$$\begin{aligned} PW &= A(1- t)(SPW - i' - N) \\ &+ (tP / Q)(SPW - i' - Q) \\ &+ tIB(SPW - i' - H) \end{aligned}$$

Thus, if there are uniform cash flows before tax and a stepped-pattern of cash flows after tax, one can find the present worth of the after-tax cash flows by means of that relatively simple equation.

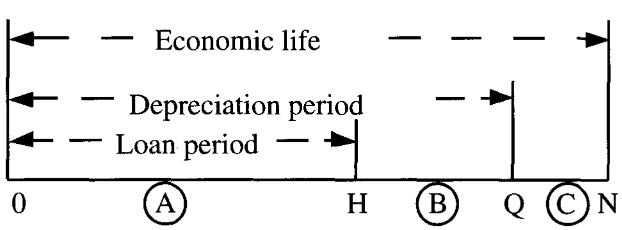


Figure 6.19

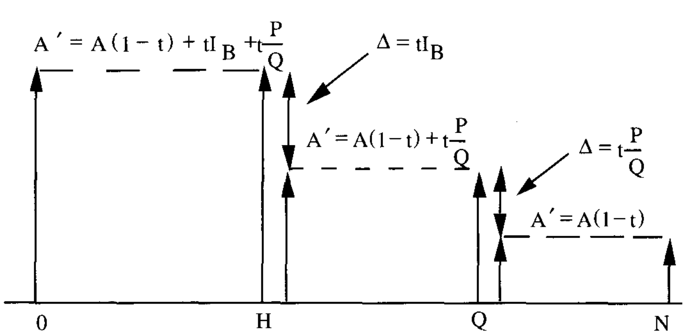


Figure 6.20

6.5.4 Residual Debt

Imagine this situation. Five years ago someone took out a \$150000 mortgage on a new house, agreeing to repay the bank in 15 equal annual payments with interest set at 12%. The annual payments were found as follows

$$A_B = \$150{,}000(CR - 12\% - 15) = \$23023$$

Now assume that a relative has died and left the person half a million dollars who is now in a position to payoff the mortgage and enjoy a debt-free home. The question then arises, how much is still owed? This answer can be obtained from the bank, but it is possible to calculate an independent check. The approach is direct and easy; at any point during an ongoing series of payments the residual debt is simply the present value of the remaining payments. In this case, 10 payments are still due, so the residual debt, P_R, will be

$$P_R = \$22\ 023(SPW - 12\% - 10) = \$124438$$

To generalize the logic developed above, let X = the number of years since the start of a loan period of H years at an interest rate iB"

The remaining years, identified as Z, will then be H - X. The residual debt will then be found this way

$$P_R = Ps(CR - i_B - H)(SPW - i_B - Z)$$

6.5.5 Balloon Mortgages

A shipowner faced with a heavy mortgage on a new ship may have difficulty in meeting the periodic payments, particularly where the loan is a major part of the total investment, that is, heavily leveraged, the repayment period is relatively brief, and the transport business is still newly developing. Under those circumstances the shipowner and bank may agree on a mortgage scheme that will require the owner to pay an appreciable portion of the debt by perhaps the ship's half life, leaving the owner responsible for paying the rest in a lump sum when that time comes. If at that time the owner cannot produce that amount of capital, there are two major options:

1. sell the ship, or
2. obtain a new loan from the same, or other, bank.

This kind of an arrangement is known as a *balloon mortgage.*

One logical way to set the amount of the residual debt, the balloon payment, is to apply the technique explained in the previous section. Consider the following example:

A shipowner wants to borrow $35 million to help pay for his proposed ship. The bank offers the loan at 10% annual interest payable over 6 years. This leads to an annual payment of $35M(CR - 10% - 6), or $8.04 million. The shipowner is worried that he might not be able to generate enough cash to pay at that rate. The bank then offers to base the payments on a 10.25% interest rate and a 1O-year schedule, but with a balloon payment due at the end of 6 years. The annual payments, A_B, will be

$$A_B = \$35M(CR - 10.25\% - 10) = \$5.75M$$

At the end of 6 years the residual debt will equal the present worth of the remaining 4 years of payments, each of $5.75 million

$$P_R = \$5.75M(SPW - 10.25\% - 4) = \$18.15M$$

As an alternative to balloon payments, some lending plans allow a period of years before the first payment falls due. This leads to some extra risk to the lender, which will have to be balanced by an increase in the interest rate, or an addition to the total debt.

6.6 MEASURES OF MERIT

6.6.1 Perspective

Up to this point this chapter has been confined to the basic principles of engineering economics. It has shown how to assess the relative values of cash exchanges that occur at different times, and how to analyze the impact of taxes and interest payments on cash flows. Now comes the critical question of how to apply all of the foregoing to decision-making in ship, or other marine product, design.

The first thing to be stressed is that there is no universally agreed upon technique for weighing the relative merits of alternative designs or strategies. Business managers, for example, may agree that the aim in designing a merchant ship should be to maximize its profitability as an investment. But they may fail to agree on how to measure profitability. Likewise, government officials who are responsible for designing non-commercial vessels, such as for military or service functions, have a hard time agreeing on how to go about deciding between alternatives. The truth of the matter is that there are good arguments in favor of each of several economic measures of merit, and the designer should understand how to handle each of them. That is what this section is all about.

6.6.2 Menu of Measures of Merit

Table 6.V identifies thirteen measures of merit, each based on sound economic principles. Each is of potential value in marine design, and several have strong adherents among people in authority. They are placed in three categories depending on whether the analyst wants to assign, versus derive, a level of income and assign, versus derive, an interest rate.

There are only three primary measures of merit; the other ten are each closely related to one of those three. Most of the rest of this sub-chapter is devoted to explaining the mechanics of each measure and when it is most suitably applied.

This introductory part is confined to the four most important measures of merit. These are the three primary measures shown in the middle column of the Table 6.V (net present value, yield, and average annual cost) plus required freight rate. The rest will be discussed later.

Marine literature contains many cost studies based on questionable logic. Perhaps the most common variety tries to minimize the unit cost of service. That is, someone looks for the alternative that minimizes the cost to the shipowner. This is technically called the *fully distributed cost.* It is something like the required freight rate, but ignores corporate income taxes and applies a rock-bottom interest rate to total capital, perhaps as low as six percent. By ignoring taxes and minimizing the time-value of money, this criterion is almost always misleading. Remember, what really counts is minimizing the cost to the customer.

6.6.3 Net Present Value (NPV)

The *net present value,* commonly abbreviated NPV, is a good place to start. It is by far the most popular of all these economic measures of merit among U.S. business managers. It is also one of the easiest to understand and use. As indicated in the table, it requires an estimate of future revenues and it assigns an interest rate for discounting future, usually after-tax, cash flows. The discount rate is usually taken as the minimum rate of return acceptable to the decision-maker. As implied by its name, NPV is simply the present value of the projected cash flow *including the investments.*

In the simple cash flow pattern, shown in Figure 6.21, K represents a uniform annual level of cash flows after tax and

TABLE 6.V Three Major Categories of Measures of Merit

Required Assumptions		*Primary Measure of Merit*	*Surrogates or Derivatives*
Revenue	*Interest Rate*		
yes	yes	NPV	NPVI, AAB, AABI
yes	no	Yield	CR, CR´, PBP
no	yes	AAC	LCC, CC, RFR, ECT

P represents a single lump investment. Given that pattern, the net present value is found by subtracting the investment from the present worth of the future cash flows. **In** short

$$NPV = K(SPW - i' - N) - P$$

With more complex cash flows, perhaps involving multi-year investments, the NPV can be found using a year-by-year table. Consider, for example, a project that is expected to involve the investments and after-tax returns shown in Figure 6.22. Assume an interest rate of 9%.

The NPV of $21.30 derived in Table 6.VII(a), being positive, would cause the proposed project to be looked upon with favor. Of course it might not be accepted if some alternative project promised an even higher value. Had the NPV turned out to be negative, the project would be given little, if any, further thought.

Table 6.VII(b) shows what would happen to the NPV or if the minimum acceptable interest rate were to be raised. Suppose one doubled it to 18%.

As the NPV is negative, the project would be rejected. What has caused the change? The answer is that the higher interest rate has strengthened the time-value of money, thus reducing the apparent benefits of future incomes.

6.6.4 Yield

An important fact to understand about NPV is that it is found by discounting future cash flows at the decision-maker's *minimum acceptable interest rate.* Because the predicted value of an acceptable project must always be positive, the actual expected interest rate will be something higher than the minimum rate used in the calculation. Instead of applying that minimum acceptable rate, one could look at the expected cash flow pattern and derive the interest rate implied.

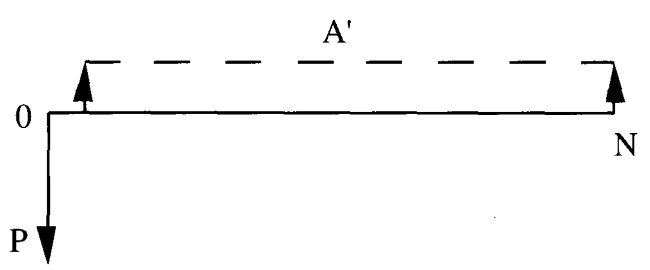


Figure 6.21

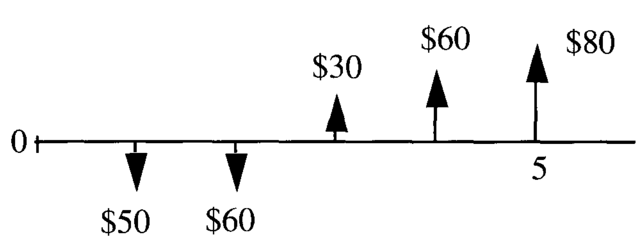


Figure 6.22

Take, for example, the projected cash flow analyzed just above. *There is some interest rate that will make the NPV equal to zero.* When that is found it will be the *yield,* sometimes called the Internal Rate of Return. The mechanics of the process are to start by selecting some arbitrary interest rate and using it to find the corresponding NPY. If the number comes out positive, the assumed rate was too low, and another calculation is made, this time with a higher interest rate. After about four repetitions the results can be plotted (NPV vs. interest rate), and the interest rate where the NPV is zero can be determined. That will be the derived *yield,* and an excellent measure of merit. Today a spreadsheet could be used to either iterate the results or to use the Goal Seek function.

Most preliminary ship design economic studies will probably not be afflicted with complex cash flow patterns, but will rather consist at a single investment, at year zero, and uniform annual after-tax returns. Take, for example, a ship with an initial cost of $30 million and uniform annual after-tax returns

TABLE 6.VII (a) Net Present Value Calculation

Year	*Cash flow*	*PW @ 9%*
1	($50)	($45.87)
2	($60)	($50.50)
3	$30	$23.17
4	$60	$42.51
5	$80	$51.99
Net present value		**$21.30**

TABLE 6.VII (b) Net Present Value Calculation

Year	*Cash flow*	*PW @ 18%*
1	($50)	($42.37)
2	($60)	($43.09)
3	$30	$18.26
4	$60	$30.95
5	$80	$34.97
Net present value		**($1.28)**

of $4.5 million. The economic life is expected to be 20 years and the disposal value can be ignored. What is the projected yield? The cash flow diagram is shown in Figure 6.23.

From the three values of initial investment, uniform returns, and period of years, the interest rate can be derived, which turns out to be about 13.9%. Otherwise, a plot on graph paper of capital recovery factors versus interest rates with contours for various numbers of years can be used.

Having derived the interest rate, or yield, of 13.9% by whatever means, it should be checked to see if that it will lead to the projected annual returns

$$\begin{aligned} A &= P(CR' - i' - N) \\ &= \$30M(CR' - 13.9\% - 20) \\ &= \$4.50 \text{ million.} \end{aligned}$$

Yield is a logical measure of merit. The popularity of the concept is reflected in the many things it is called. Among these are; *Discounted cash flow rate of return, Internally generated interest, Rate of return, Profitability index, Percentage return, Investor's method, and Equivalent return on investment.*

Some advocates of NPV point to situations where yield may be misleading.

One of its shortcomings may show up if one is faced with a cash flow pattern that shows a year-by-year mix of money coming in or out. That being the case, it may turn out that there is more than one interest rate that will bring the net present value down to zero. In short, the analysis has predicted more than one yield and no hint as to which to believe. Fortunately, most ship economic studies involve simple cash flow patterns in which that dilemma does not arise.

A more serious flaw is that yield is fundamentally a less accurate measure of human satisfaction, which is what engineering economy is all about. Suppose a person's instincts are such that they cannot decide between having $100 today or the firm promise of $120 a year from now. That establishes the individual's private internal time value of money as being equivalent to 20% annual interest. Now suppose someone offers the person two mutually exclusive opportunities to invest $100 today. Proposal A will return $200 a year from now. Proposal B will return $300 two years from now. Since the $100 investment is the same in both proposals it can be ignored. Then the person could look a year into the future and ask whether at that time it would be better to

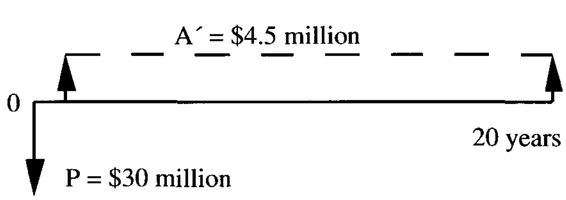


Figure 6.23

accept the promised $200 right then or the promise of $300 in another year. Applying the NPV criterion, the benefit of accepting Proposal B instead of A would be:

$$NPV = (PW - 20\% - 1)\$300 - \$200 = \$250 - \$200 = \$50.$$

Those numbers lend quantitative evidence to what should have been obvious: the second alternative is the more desirable. However, suppose yield was used as the criterion. That would lead to these calculations. For Proposal A

$$F / P = \$200 / \$100 = 2.00 \text{ and } N = 1$$

The corresponding yield = 100%.

For Proposal B

$$F / P = \$300 / \$100 = 3.00 \text{ and } N = 2$$

The corresponding yield can be found thus

$$\begin{aligned} (1 + i)^2 &= 3 \\ 1 + i &= 3^{0.5} \\ i &= 73.2\% \end{aligned}$$

This shows that the yield criterion would favor Proposal A, which is clearly less desirable to anyone whose instinctive time-value of money amounts to 20% interest.

Being a little more sophisticated it could be asked, *Suppose a person were to accept Proposal A and at the end of the year reinvest it in an equally profitable way?* That means doubling it again, so the initial $100 would grow to $400 at the end of the second year. But, if reinvestment is assumed for A it must also be assumed for B. These reinvestments might, in theory, go on forever. Now these imaginary investments can be compared on the basis of their cumulative present worth's. To find those values, divide each average annual cost by the interest rate, namely 20%. Again, the initial investments being identical can be dropPed.

For A the cumulative present worth for $200 per year going on forever

$$PW \text{ of } A = AAC / i = \$200 / 0.2 = \$1000$$

For B one would first need to convert $300 every other year to an equivalent annual amount by multiplying by the sinking fund factor for 20 percent interest and two years. Then divide that by the interest rate

$$PW \text{ of } B = (SF - 20\% - 2)\$300 / 0.2 = \$681.82$$

Now Proposal A looks better. From this one can conclude that yield may be superior to NPV if continuing reinvestments at the same level of profitability can be assumed.

What does all this prove? One reasonable conclusion is that each measure of merit is as worthy as the other. As someone once observed, those who prefer NPV want to make money so as to exist. Those who prefer yield exist to make money. This reflects the different philosophies of the corporate executive and the entrepreneur.

6.6.5 Average Annual Cost (AAC)

The next measure of merit is useful in designing ships that are not expected to generate income: naval vessels, Coast Guard vessels, and yachts immediately come to mind. Now the cash flow pattern will feature only money flowing out. When that is the case, a logical and popular measure of merit is called *average annual cost* (AAC). The simplest case would have a single initial investment (P) at time zero, and uniform annual operating expenses (Y) for N years thereafter, as shown in Figure 6.24.

In the preceding example, the average annual cost would be found by converting the initial investment, P, to an equivalent uniform annual amount, which would be added to the annual operating costs, Y

$$AAC = P(CR - i - N) + Y$$

The interest rate should be some logical measure of the decision maker's time-value of money. In the case of a government-owned ship it might reflect the current rate of interest paid on government bonds.

Whereas in using NPV or yield, one seeks the alternative promising highest values, in using AAC, the lowest values are desired.

Average annual cost also may be applied to commercial ship designs where all alternatives would happen to have equal incomes.

For example, find the average annual cost for a proposed oceanographic research vessel that is projected to cost $12 million to buy and $3 million per year to operate. The expected life is 25 years and an interest rate of 12% will apply. Using the equation developed above, we have

$$\begin{aligned} AAC &= \$12M(CR - 12\% - 25) + \$3M \\ &= \$1.53M + \$3M = \$4.53 \text{ million} \end{aligned}$$

For more complex cash flows, simply discount everything back to year zero, (including the initial investment), then multiply the total figure by the capital recovery factor. That will produce the average annual cost.

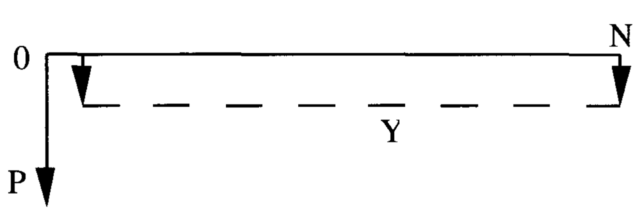


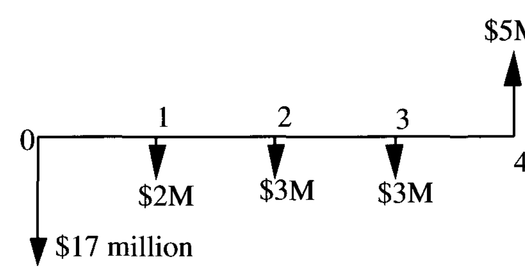
Figure 6.24

Consider another example: A survey ship is expected to cost $17 million. Its operating costs will come to $2 million in the first year, $3 million in the second and third years, and $4 million in the fourth year. After that it is to be sold at an expected net resale value of $9 million (leading to a net inflow of $5 million in year four). An interest rate of 15% is stipulated. The cash flow pattern is shown in Figure 6.25, together with a table showing year-by-year present values. Notice in this case that any positive cash flow, such as that resulting from the resale, is treated as a negative cost.

Another approach is to develop a new effectivness metric such as days on patrol/ships inspected. Then a cost-effectiveness ranking can be derived by dividing the effectiveness metric by the AAC or vice versa.

6.6.6 Required Freight Rate (RFR)

Suppose two competitive designs promise the same average annual cost, but vessel B promises to be more productive than vessel A. Clearly that should tip the scales in B's favor. This difference is quantified by relating the AAC to productivity. In the case of cargo ships this is done by dividing the average annual cost by the tons of cargo that could be carried each year on some particular trade route. This gives us the *requiredfreight rate* (RFR). The same concept could be applied to other measures of productivity such as automobiles per year for a ferry, tons of fish per year for a trawler, passengers per year for a passenger ship, and so forth.



Year	*Cash flow*	*PW @ 15%*
0	$17M	$17.00M
1	$2M	$1.74M
2	$3M	$2.27M
3	$3M	$1.97M
4	($5M)	($2.86M)
Total present worth		$20.12M

AAC = $20.12M(CR – 15% – 4) = $7.05 million (rounded)

Figure 6.25

Assuming a single invested amount (P) at year zero, uniform annual operating costs (Y), and annual tons of cargo (C), the equation for required freight rate becomes

$$RFR = AAC / C = [P(CR - i - N) + Y] / C$$

Choosing an interest rate here is tricky. Assuming free market forces at play and all competitors facing equal costs, the interest rate should be just high enough to bring a balance between demand for transport service on the trade route in question and the supply of ships capable of providing that service. Higher rates would attract too many ships; lower rates would drive ships to other services. Adam Smith called this the *natural rate.* It is closely akin to what economists today call the *shadow rate.*

What is the significance of RFR? It is the rate the shipowner must charge the customer if the shipowner is to earn a *reasonable* return on the investment. The theory is that the owner who can enter a given trade route with a ship offering the lowest RFR will best be able to compete.

A key step in finding RFR is to convert the initial investment to an equivalent uniform annual negative cash flow before tax. These annual amounts must be large enough to pay the income tax, and return the original investment to the owner at the specified level of interest. In short, a suitable value for the capital recovery factor before tax must be found. To do this, use the basic relationship between cash flows before and after tax explained in Subsection 6.4.5

$$A' = A(1 - t) + tP / N$$

To make this non-dimensional, divide through by the initial investment, P

$$A' / P = A(1 - t) / P + t/ N$$

But

$$A' / P = CR'' \text{ and } A / P = CR$$

which leads to

$$CR' = CR(1 - t) + t/ N$$

Then, solving for CR

$$CR = (CR' - t / N) / (1 - t)$$

This, then, is a simple way of converting an after-tax interest rate to a before-tax capital recovery factor. It assumes an all-equity investment and a tax depreciation period equal to the ship's economic life. More complex relationships are discussed later on.

To clarify this consider the following example:

Assume a proposed ship that can move 3.5 million tons of cargo over a given trade route each year. Its estimated first cost is $40 million. Its economic life is set at 20 years. The tax rate is 45%. The annual operating costs are ~timated at $2.5 million. The owner stipulates a yield of 1'2%. What is this ship's required freight rate?

Start by finding the after-tax capital recovery factor based on 12% interest and 20-year life

$$CR' = (CR - 12\% - 20) = 0.1339$$

This leads to

$$\begin{aligned} CR &= (CR' - t / N) / (1- t) \\ &= (0.1339 - 0.45/20) / (1 - 0.45) \\ &= 0.2025 \end{aligned}$$

and finally,

$$\begin{aligned} RFR &= [P(CR) + Y] / C \\ &= (\$40M(0.2025) + \$2.5M) / \$3.5M \\ &= \$3.03 \text{ per ton.} \end{aligned}$$

Having found the required freight rate, the problem can be reversed by starting with the RFR and deriving the attainable yield. Here is how an accountant would handle the job:

Annual revenue = $3.03x3.5M tons	$1O.605M
Annual operating costs	$2.500M
Annual cash flow before tax	$8. 105M
Depreciation: $40M / 20	$2.000M
Annual tax base	$6. 105M
Tax @ 45%	$2.747M
Annual cash flow after tax	$5.358M
After-tax capital recovery factor	0.1339
Corresponding after-tax yield	12%

which agrees with the initial specification.

This bears out the soundness of the way shown above for converting from an after-tax yield to a before-tax level of income.

Remember that the after-tax cash flow is found by subtracting the tax from the before-tax cash flow as shown in the preceding table.

6.6.7 Net Present Value Index (NPVI)

Despite its popularity, net present value (NPV) can lead to faulty decisions unless used with care. One weakness arises from it being dimensionally-dependent. As a result, it will always tend to favor large proposals even though smaller, more numerous proposals might well lead to greater cumulative NPV s, assuming that the supply of investment dollars is limited. To correct that weakness, simply divide each proposal's NPV by the investment: NPV / P. This may be called the *net present value index,* abbreviated NPVI.

6.6.8 Average Annual Benefit (AAB)

A second weakness of NPV is that it makes unfair comparisons between long and short-term investments. Consider a new ship with a projected life of 20 years that is in competition with a secondhand ship with a projected life of, say, 10 years. If the new ship's NPV is estimated to be $20 million, and the second-hand ship's $15 million, what does that prove? The comparison is obviously unfair because the secondhand ship, after 10 years could presumably be replaced with another old ship and that would add to the NPV of the second-hand ship option. The standard approach to such comparisons is to develop the NPV for a succession of identical units. In this case we should add to the first ship's $15 million NPV the present worth of a like amount 10 years in the future.

The approach outlined here is easy enough when the competing lives have some neat common multiple. But suppose the secondhand ship has a projected life of, say, 8 years? That being the case, a valid comparison can be made by converting each projected NPV to a uniform annual income stream of equivalent value. To do this, simply multiply the present amount by the capital recovery factor (CR) appropriate to the unit's expected life and the interest rate used in finding NPY. This uniform amount is called the *average annual benefit* (AAB). Note it's exact parallel to average annual cost, AAC. Moreover, like AAC, it automatically corrects for differing life expectancies, because each succeeding unit must be assumed to have the same average annual cost on into infinity.

6.6.9 Average Annual Benefit Index (AABI)

The NPV's two weaknesses can be overcome simultaneously by dividing the average annual benefit (AAB) by the investment to give the average annual benefit per dollar investment. This is called the *average annual benefit index* (AABI).

These three variations on NPV are such obvious common sense corrections that they are commonly used without attaching names to them.

When comparing two alternatives where initial investments are unequal, some analysts consider what use would be made of the savings if the less expensive option were chosen. Similarly, if lives differ, they would project the cash flow arising from the replacement of the shorter-lived option. This kind of approach allows reliance on NPV without the corrections involved in NPVI, AAB, or AABI. Although reasonable when comparing limited numbers of alternatives, such approaches would be ill fitted in preliminary design studies involving large numbers of choices.

6.6.10 Capital Recovery Factor After Tax

As pointed out in Subsection 6.6.4, in most preliminary design studies it is usual to assume the simplest possible cash flow pattern: a single investment made on the day of delivery, and uniform annual after-tax returns. Such a pattern hinges on several other assumptions:

- the tax depreciation period equals the economic life of the ship.
- taxes are based on straight-line depreciation.
- the ship's net disposal value will be zero.
- there are no bank loans or bonded debt. That is, an all-equity investment.
- no working capital is required. For example, temporary cash paid out, but to be recovered later - like a key deposit.
- no fancy tax-softening schemes, such as, tax credit or tax deferral are used.
- revenues and operating costs will both remain uniform throughout the economic life, after adjustment for inflation.
- there are no major components, for example, cargo containers, with an economic life that differs from that of the ship.

Admittedly these are exceedingly bold assumptions. Yet, in the majority of ship economic studies they are reasonably safe because the errors induced tend to be the same for all alternatives. *Remember, in choosing between alternatives, it's the differences that count.* As mentioned before, some shipowners and/or their accountants will want to embellish the naval architect's estimates with all manner of elaborate complications. Under those circumstances, the naval architect is well advised to seek a compromise. However, the analysis should start out with the simplifying assumptions that lead to the neat cash flow pattern shown in Subsection 6.6.4.

Given that simple pattern, the yield can be found, as previously explained, by first finding the capital recovery factor after tax

$$CR' = A' / P$$

and then, finding the interest rate corresponding to that capital recovery factor and the assumed years of life. That rate (i') would be the investment's yield.

A cursory look at interest tables will show that the alternative design promising the highest capital recovery factor after tax will automatically promise the highest yield. In short, CR' is a valid surrogate for yield (if all the above simplifying assumptions are accepted) and is just a little easier to find.

6.6.11 Pay-back Period (PBP)

Another related measure of merit is the payback period (PBP), which answers the entrepreneur's invariable question: how soon is the investment repaid? Assuming uniform annual returns, the answer is easily supplied

$$PBP = P / A$$

This is the reciprocal ofCR' and so incorporates all that criterion's strengths and weaknesses. Its main problem is that it has often been misused (ignoring comparative cash flows that may occur after the pay-back period) and has acquired an unsavory reputation. It does not provide any more guidance than CR' or yield.

6.6.12 life Cycle Cost (LCC)

In non-income producing projects, some analysts use a criterion consisting of the initial cost plus the cumulative value of the discounted future costs. This is usually called *life cycle costs* (LCC). With uniform operating costs

$$LCC = P + Y(SPW - i - N)$$

Whereas average annual cost (AAC) totals all present and discounted future costs and then spreads them out into a uniform annual stream of equivalent value, LCC simply brings everything back to the present. If all the alternatives have equal lives, then LCC and AAC will lead to the same conclusion as to which alternative is best. If lives differ, however, LCC will be unreliable. Life cycle cost is inferior to average annual cost in range of applicability, which suggests that it not be used.

Some people have trouble telling the difference between NPV and LCe. There are two important differences. NPV applies to cases where incomes can be predicted. LCC applies to cases where either there is no income, or all alternatives have equal incomes. NPV discounts future amounts based on a minimum acceptable interest rate. LCC use a somewhat higher, target rate.

6.6.13 Capital Recovery Factor Before Tax as a Measure of Merit

Subsection 6.6.1 shows that under a set of commonly assumed circumstances the capital recovery factor after tax (CR') could serve as a reliable surrogate for yield. One of those common assumptions was that the tax would be based on straight-line depreciation with tax life equal to the economic life. Given that, the capital recovery factors before and after tax would be related as follows

$$CR' = CR(1- t) + ti N$$

If all alternatives have equal lives (N), and since the tax rate (t) would be the same for all, it becomes clear thatthe alternative promising highest capital recovery before'Jax would also promise the highest capital recovery factor after tax. Further, then, it can be concluded that capital recovery factor before tax is a valid surrogate for yield, as long as all those standard simplifying assumptions hold true. **In** short, the simple ratio of before-tax returns to first cost can serve as a reliable measure of merit

$$CR = A / P$$

6.6.14 Economic Cost of Transport

Ifthe ships under study are to carry a high-value cargo, then the required freight rate (RFR) could be adjusted in recognition of the inventory value of the goods in transit. If this is done, the faster ships will receive deserved credit for reducing the time the merchant's investment is tied up. This adjusted freight rate is called the *economic cost of transport* (ECT). Its value can be derived from this expression

$$ECT = RFR + [ivd / (1 - t) 365]$$

6.6.15 Capitalized Cost

This is a measure of merit that is seldom used in maritime studies, but was once popular in civil engineering circles and is sometimes mentioned in the literature. It assumes that each alternative, as it is retired, will be replaced by an exactly identical unit, and that all costs (both capital and operating) will remain forever the same. Called *capitalized cost, it* is simply the present value of the perpetual series of cash flows stretching into infinity. One might think that an infinite stream of money might add up to an infinite amount. And so it would were it not for the time-value of money and those discount factors one must apply to the future amounts.

With a little analytical thought one can conclude, correctly, that the capitalized cost of an infinite stream is simply the average annual cost of the first unit divided by the interest rate used in finding that AAe.

6.6.16 Yield and NPVI: A Special Relationship

Most preliminary design studies apply the standard simplifying assumptions that lead to simple cash flow patterns like that shown in Figure 6.26.

Given that the above pattern applies to all alternatives, then the best chosen on the basis of yield will also be the best chosen on the basis of net present value index. This is explained by the following analysis.

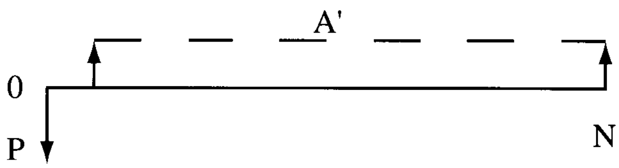


Figure 6.26

By definition, the NPVI equals the net present value divided by the investment

$$NPVI = NPV / P$$

but

$$NPV = (SPW - i' - N)A - P$$

so

$$NPVI = [(SPW - i' - N)A / P] - I$$

but

$$A / P = CR'$$

therefore

$$NPVI = (SPW - i' - N)CR' - I$$

Since the interest rate (i') and years of life (N) should be the same for all alternatives, it follows that the series present worth factor (SPW) should also be the same. Thus the best alternative will hinge on which one has the highest after-tax capital recovery factor (CR'), which will automatically be the one producing the highest yield. This shows that NPVI and yield will lead to the same design decision. This explains a nice peculiarity of NPVI: it shows the same point of optimality regardless of the discount rate assigned.

As pointed out in Subsection 6.3.6.2, SPW and CR are reciprocals. This might lead one to look at that last equation and conclude that NPVI should equal one minus one, or zero. This is not the case, however, because as here defined, CR' is derived (from estimated values of A and P), while SPW is based on an assigned interest rate, which would usually be something less than that corresponding to CR'.

6.6.17 Ships in Service

If financed on credit, as is most common for commercial ship loan repayments, the interest may exert a large influence on ship operations in the early years of a ship's life. However, once a ship has been paid for, the first cost (P) is no longer a variable and should therefore be ignored in making decisions about its operation. Maximizing profitability now hinges simply on maximizing the annual difference between income and operating costs. In doing this, one should take a long-term view and not try to save money by neglecting maintenance and repairs.

6.7 CONSTRUCTING THE ANALYSIS

6.7.1 Perspective

Having assimilated the principles of engineering economics, the naval architect/designer must next develop rational methods for applying them to real-life. While there are few immutable, all-purpose rules that can be laid out (1-7), an effort should be made to develop a feeling for constructing engineering economic comparisons that will lead to wise decisions in choosing between design alternatives. However, there is no substitute for learning to think for oneself and the intent here, is simply to provide a starting point.

In working through the innumerable steps involved in economic analyses it may become all too easy to be so overwhelmed by details that the central aim of the study is forgotten. As already stated, naval architects may find that they are dealing with accountants who require more complex investigation (I). They may also appear to want unreasonable accuracy for the profitability of each alternative. In contrast, the naval architect/designer wants principally to rank the alternatives, that is, to show which ones promise to be most profitable. In most cases relatively simple approaches will suit such needs. Accounting elaborations will tend to confuse the situation and needlessly burden the analysis. The logical compromise is to use simple, qualitative methods to narrow the field of contenders, and then satisfy the accountants by applying their quantitative methods only to the more promising candidates.

Most of what follows stresses the design of merchant ships. Much of what is said, however, can be modified to apply to all manner of engineering concepts.

6.7.2 Know the Goal

The aim in all this is to sell to some prospective shipowner some strategy, say a ship design, for maximizing the profitability of his or her investment. Right from the start, learn the owner's preferred measure of merit and be ready to deal in those terms.

Along with learning the preferred measure of merit, the shipowner's functional needs must be determined and under what constraints the project must operate, as described in detail in Chapters 4 and 7. There are other details to be learned from the owner: tax rate, depreciation plan, interest rates, perhaps charter rates, and so forth. If any of those figures are confidential, the shipowner should still be willing to bracket them in upper and lower values.

The shipowner should be explicit as to the form in which the cargo is to be moved, bulk, break-bulk, on pallets, in containers, etc. The details of the pertinent port facilities also must be obtained. If these do not yet exist, the definition of the system should be expanded to include the design and operation of the terminals as well as the ships. This leads to the next sub-section.

6.7.3 Define the System

To reach proper decisions logical boundaries of the system must be set. They should be chosen so that design decisions would have little if any effect on the rest of the enterprise (or the outside world, for that matter). For examples return to and review the iron ore transport problem outlined in Sub-section 6.2.3.

6.7.4 Be Prepared

For a successful career in design it is necessary to continually strive to collect data on weights, building costs, operating costs, and income potential. Naval architects/designers must also learn how to use such data to predict the profitability potential of competing design alternatives. How to use such data is the purpose of this section.

6.7.5 Selecting the Structure

By way of preface to this topic, it appears that, in general, the more important the decision; the less applicable are sophisticated analyses. This does not mean that rational decision-making methods should be ignored. Rather it only points to the logic of selecting an appropriate degree of sophistication.

There are situations in which only two alternatives need be considered. An example would be technical feasibility studies such as coal versus oil for ship propulsion. Here feasibility may be established by comparing one well thought-out challenger (coal) against one equally well thought-out defender (oil). In doing this, select an operating environment that favors the challenger. Then, if the challenger fails to measure up to the defender the decision maker is probably safe in deciding against the challenger. If the challenger looks good under those favorable circumstances, then one can seek to expand the operating environment in which it offers promise.

In more thorough feasibility studies the naval architect should seek to optimize both challenger and defender (by considering many alternatives in each) and then let each camp be championed by its own best contender. If this seems too obvious to be worth saying, note that the marine literature includes many published studies where this common sense rule is ignored.

In optimizing the design of a merchant ship, the lOgical procedure will hinge first of all on whether the size is to be limited by external constraints (allowable draft or limits on overall dimensions) or by the availability of cargo, passengers, or whatever the ship is to transport.

Consider first the case where cargo comes in virtually unlimited supply. Examples include most bulk commodities such as crude oil, iron ore, and grain. In ships for such cargoes the cardinal rule is the bigger the better. There are all manner of economic benefits in making them as big as external constraints will reasonably allow. It is wrong to start with an arbitrarily established deadweight or cargo capacity. Those characteristics should drop out at the end and not affect thinking along the line. In most bulk trades the same is true of sea speed. Frequently the only important external constraint will be the allowable draft. That being the case, maximum values of length, beam and depth will be determined by reasonableness of proportions. However, certain ports and transit of canals can set length and beam constraints. Chapter 11 describes how the design of the ship can then be undertaken.

The economics of each combination will need to be predicted. Keep in mind that most liner operators like to offer easily remembered sailings, such as every Friday or every other Friday, from a given port.

This brings up the matter of the economics of speed in the liner trades. Today Freight Agreements are most common, which set the freight rate. Some liner operators still belong to *ocean conferences* (cartels) that set freight rates, and these are fixed regardless of quality of service. Competition comes, then, in trying to offer the best service, including speed of delivery. Thus, high speed, although fundamentally uneconomic, may be highly profitable. There is little the naval architect can do to make an issue of optimum speed under such conditions. The shipowner will have the desired speed as one of the requirements.

6.7.6 Selecting an Interest Rate

Some of the valid measures of merit require an assumption as to interest rates. In real life some business manager may dictate what that figure should be. On the other hand, a naval architect may have to select the rate. So, the question arises; what is a reasonable rate? Under U.S. economic conditions, a ship operating company that wants to attract equity capital through the sale of stocks, or borrow money from a bank at minimum commercial rates, probably will aim for a minimum yield on total capital of ten to fifteen percent in constant-value terms, although the current international shipping economics does not support such high levels. Captive fleets with secure sources of income might favor the lower figure; common carriers might favor the higher.

Even the federal government should recognize the time-value of money. The exact figure is hard to pin down. Some experts base it on the interest paid on government bonds, which is remarkably low when corrected for inflation.

If net present value is the criterion of choice, the analyst will want to select a minimum acceptable interest rate. Business managers usually base this on the average cost of capital. If they raise half of their capital through selling stock (on which they hope to pay dividends of twelve percent) and half through bank loans (on which they pay eight percent interest) they might take the weighted average of those figures and thus discount future amounts at ten percent. They might also add 1/2 to 1% for margin.

Do not go overboard on trying to lower overall interest rates through extensive borrowing. The fact is that the more one borrows from a bank, the greater is the risk being placed on both the bank and the equity holders. Both, then, have the right to insist on higher rates of return. The net effect is that overall rates should remain about the same regardless of source of capital.

Keep in mind that that these considerations are all in terms of constant-value dollars. It can be considered, in effect, that inflation or deflation will not occur. As long as the shipowner is free to change freight rates to reflect changing costs, that is a reasonably safe assumption.

6.7.7 Analyzing Differences

Suppose it is required to choose between two alternatives both of which have equal annual incomes, (including the possibility that both are zero), and the alternative with the higher first cost will have lower operating costs. The question then arises: if the one with higher first cost is chosen, will that higher cost (ΔP) be more than offset by the future savings in operating costs (ΔY)? If taxes are involved, the annual saving in operating cost will be reduced by the amount of the tax, but tempered by the increased depreciation allowance. The net gain in annual cash flow after tax ($\Delta A'$) will then be

$$\Delta A' = \Delta Y(1 - t) + t\,\Delta P / N$$

Some economists apply the same concept to multiple-choice situations, such as optimization studies. To do this, they rank the alternatives in order of ascending first costs. They typically use NPV to analyze the benefit of going from first to second alternative. If that meets their standard of profitability, they go on and look at the benefit of going from the second step to the third, and so forth until the incremental cash flow is no longer great enough to justify the incremental investment. There are settings where this approach is satisfactory; there are others where it is not. Its fundamental weakness shows up perhaps most clearly when NPV is the criterion. If one keeps increasing the first cost, the NPV of the differences will be large at first and will diminish as one advances up the scale. When at last it shrinks to zero, and that point on the design scale is selected, it will in effect settle on a design that promises minimum acceptable profitability. But that is not what NPV is all about. NPV aims to find the alternative that will *exceed* the minimum acceptable level of profitability by the greatest margin. What this means is that the incremental approach will almost always lead to overdesign.

6.7.8 Planning Horizons

Naval architects may need to analyze the economics of complex systems that incorporate a variety of facilities, each with a different economic life. An example is a container transport system involving terminals and their cranes as well as ships and containers. Life expectancies may vary from 10 years for the containers to 20 for the ships to 25 for the cranes to 50 for the buildings to infinity for the real estate. To find the complete system's NPV, for example, how far into the future should one look? Most economists will simply select an arbitrary cut-off date at some intermediate time, perhaps 20 or 25 years. If the analyst is troubled by the thought of dropping the curtain 25 years from now on a replacement ship that will then be only 5 years old, the ship's potential resale value could be introduced as a positive cash flow at that time. Remember that those future cash flows are going to be severely discounted, so gross oversights need be of little concern.

6.7.9 Residual Values

At any point during the life of a ship it has a residual or disposal value. For example, how much hull and machinery insurance should be applied to an old ship? Enough to buy an equivalent new ship? The original cost of the old ship? Neither of those. The insurance should be high enough to cover the present worth of the projected after-tax cash flows over the presumed remaining years of life. That is all that is needed to protect the investment.

The same kind of thinking should be applied to negotiating the sale price of an existing ship.

6.7.10 Replacement Analysis

When should a shipowner replace a capital asset? Shipowners should ask that question from the moment the construction contract is signed. During anticipated increases in demand, some speculators sign contracts with every intent of selling them to a less far-seeing owner before the ship is even built. As the ship enters service the owner should at least once a year ask the question, *should the ship be sold today or should a year go by before repeating the question?* If the owner decides to keep the ship, the owner will be foregoing the immediate net (after-tax, etc.) income, a lost opportunity cost, abbreviated Po. That may be justified by the expectation of receiving a net after-tax income a year from now. That year-off income will be made up of three components:

1. the after-tax cash flow from one more year of operation: *K*,
2. the net income from selling the ship a year from now: LI' and
3. the hidden after-tax costs of inferiority: Z

Inferiority has four components:

1. deteriorated condition of the existing ship leading to: lessened income and increased operating costs,
2. lost opportunity costs of not owning the better ship available today,
3. increased income potential, and
4. reduced operating costs

The shipowner could visualize the cash flow pattern as shown in Figure 6.27.

Now the shipowner is ready to decide whether keeping the ship for another year is worth doing. The measure of merit will be NPV. If it comes out positive, that would encourage keeping the ship for at least another year; otherwise it should probably be sold. The general equation will be

$$NPV = (PW - i' - 1)(A' + L_1 - Z) - P_0$$

Several other analytical techniques have been proposed by others, but the one outlined above is the simplest and, quite possibly, most satisfactory. Needless to say, it involves a lot of educated guesswork about the future, but that is a feature of nearly every element of engineering economics.

6.7.11 Predicting Economic Life

The preceding sub-section talks about deciding on a year-by-year basis when to retire an existing ship. But, in designing a ship, every economic criterion requires an estimate of how long the ship should last. That is a more difficult task, but, fortunately, a less critical one. One method tries to look ahead to the changing patterns of the various components entering into the replacement analysis explained above. It then tries to predict at what future time the year-

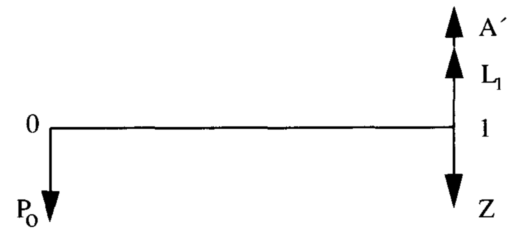


Figure 6.27

off cash flow will no longer be enough to offset the advantage of immediate sale.

There are other approaches. In one of them the analyst predicts future cash flows and tries to find the total years of operation that will maximize the average annual benefit. Another uses dynamic programming to analyze possible cash flows in a massive decision tree with a time base stretching over many decades.

In real practice the exact time that a ship will be disposed of is influenced by anticipated major repair costs, such as at the second or third five-year special survey.

6.7.12 Uncertainty

Economic studies are built on a foundation of estimates of future costs, incomes, and operating conditions. Nearly every element of the analysis may prove wrong in actual fact. This leads to the conclusion that any complete economic projection should consider the impact of various alternative assumptions about future conditions. The concepts of risk and probability are used to take the uncertainty into account and to provide better information on which the decisions can be made. Standard texts on business management may be consulted for details.

If an economic study considers large numbers of alternatives, the analysis would normally start out using only single most likely values of each parameter (this is called the *deterministic approach).* The more elaborate procedures mentioned above would be applied only to the final few contenders. This is simply a matter of keeping the computationalload within reason.

Spreadsheets can be used, which allow the user to specify a statistical function for any value, such as freight rate. Results will then be presented as a range of metrics, say NPV s.

6.7.13 The Benign Influence of Flat laxity

The *termfiat laxity* refers to the characteristic shape oftypical ship optimization curves. These show that one may select a design characteristic that is several percent above or below the theoretical point of optimality with only negligible loss in economic efficiency. This leads to the conclusion that intangible factors may be allowed to push the design well away from the indicated optimum without great loss in economic benefit. One can also conclude that advocates of different measures of merit should be able to agree on compromise decisions. The exception to this comes in cases where abrupt discontinuities are involved, such as a switch from single screw to twin screw propulsion, or in feasibility studies involving differing technologies.

6.8 BUILDING COSTS

6.8.1 Perspective

Engineering economic studies almost always involve an estimate of invested costs. Indeed, the first cost of a project is usually the single largest, hence most important, factor entering into the study. Although shipbuilding costs may be estimated for several different reasons, this chapter will concentrate on only one, which is to help make rational decisions in preliminary design. For detailed discussion on Cost Estimating see Chapter 10.

First, an important disclaimer: this section is *not* a cookbook that can be used to predict costs. It is, rather, an explanation of how one can structure a procedure for estimating the costs of alternative design concepts. Naval architects will need to complement what is explained here with appropriate real-life data collected from many various sources. A few useful publications are given in the references (6,7), but even the best of them go quickly out of date (8-10).

6.8.2 What is Important?

In preliminary ship design naval architects normally want to predict the economics of large numbers of alternative designs (see reference 1). This means that the estimating methods should be relatively simple. Also the data on which they are based should be easily collected. The alternatives under consideration usually exist only as imaginary concepts about which few details have been established. This, too, suggests that the techniques must be relatively simple. Moreover, except in rare cases, it is not necessary to worry about exact costs; relative costs are what matter. This suggests that the estimating methods should strive to emphasize *differences* in costs between the various alternatives. Absolutely accurate costs are seldom necessary and are difficult to predict.

6.8.3 Two Common Bases

Most cost estimating techniques boil down to questions of costs related to some understandable characteristic of the subject under study. These characteristics fall into two major categories: functional capability such as deadweight and speed, or technical characteristics such as major dimensions' and power. The second family of techniques is usually better suited to design purposes and it is on them that most of this discussion will be concentrated. But, to start, a brieflook at the first group is appropriate.

6.8.4 Functional Capability as a Costing Basis

Among shipowners, a popular estimating rule of thumb is to talk about shipbuilding costs in terms of so many dollars per ton of deadweight. This answers two questions of paramount importance to the prospective owner of a merchant ship: how much can it carry and how much will it cost? The estimating technique may take a form such as

$$P = C_1(DWT)^B$$

where C_j is a coefficient, B is an exponent typically about 0.7 to 0.8, and both are derived from known data on similar ships.

Needless to say, such methods will be highly unreliable unless confined to ships closely akin to those that served as sources of data. They lack the versatility needed for most preliminary design studies.

6.8.5 Technical Characteristics as a Costing Basis

Perhaps the simplest technical characteristic to use as a basis for estimating cost is the light ship weight (WE). That, after all, is the single most basic measure of what the owner buys. Aeronautical engineers have concluded that the cost of almost any kind of vehicle could be approximated by means of the simple expression

$$P = C(W_E)^{0.87}$$

Again, such a simple approach has its limitations, but can be useful in situations where returned costs are rare, such as in newly developing kinds of vehicles.

As discussed in Chapter 10, when shipyard cost estimators prepare a bid for a proposed ship, they, too, look at unit costs based on technical characteristics. But now, rather than basing their work on a single characteristic, they look at one part of the ship at a time and try to predict both material and labor costs for building each part. Typically, they may make individual estimates for about 200 physical components of the finished ship. Most of their unit costs are based on weights, which can be fairly accurately predicted during the bidding phase. In preliminary design work, however, not enough is known about the ship to go into such detail. Some simplification is needed. Some examples are given below.

In the early design stages, before any drawings have been prepared, the alternative designs are in the form of concepts about which nothing is known beyond perhaps the principal dimensions and power. The ship can be broken down into two parts: hull and machinery. Hull costs can be based on the cubic number (CN) and machinery costs on power (usually BHP). This might lead to this expression for first cost (P)

where

$$CN = L \times B \times D / 100$$

C_1 and C_2 are coefficients, and E and F are an exponents, all of which are derived from previous similar ships.

Again, such simple methods become wildly inaccurate unless narrowly confined. Confidence can be increased if one applies techniques that are considerably more accurate and yet require no more knowledge about the alternative ships than what is implied above: main dimensions, power, and perhaps block coefficient. To do this the naval architect could break the ship down into three major parts, namely: structural hull, outfitting plus hull engineering, and machinery. In addition expenses can be divided between material, labor, and overhead. Labor rate should include allowances for benefits and other indirect costs. Normally, material and labor costs for each of the three major components are estimated, to which overhead is applied as a single, overall cost.

The first step is to estimate the structural hull component weights based on the cubic number. Cubic number is also used to predict material and labor costs for hull and outfit including hull engineering. Machinery material and labor costs may be based directly on BHP.

Tables 6.VIII and 6.IX, taken from reference 3, is a typical example of a cost estimate based on the sort of technique described just above.

Its degree of elaboration is sufficient to give reasonably accurate estimates, and yet simple enough to allow one to analyze hundreds of alternative designs (assuming access to computer).

TABLE 6.VIII Simple Cost Estimate

Ship component	*Material*	*Labor man-hours*
Structural hull	$\$375W_s$ $= \$375 \times 3900$ $= \$1.46M$	$80(W_s)^{0.90}$ $= 80(3900)^{0.90}$ $= 136\,000$
Outfitting and hull engineering	$\$3500W_O$ $\$3500 \times 1800$ $= \$6.30M$	$95W_O$ $= 95 \times 1800$ $= 171\,000$
Machinery	$\$6000(BHP)^{0.7} + \$3M$ $= \$6000(12\,800)^{0.7} + \$3M$ $= \$7.50M$	$200(BHP)^{0.7}$ $= 200(12\,800)^{0.7}$ $= 150\,000$
TOTAL	$15.26 M	457 000

Notes
W_s = weight of structural steel (net) = 3900 tonnes.
W_O = weight of outfitting and hull engineering = 1800 tonnes.
BHP = maximum continuous rating brake horsepower = 12 800.
Hourly labor rate = $10; overhead cost = 85% of labor cost.
M = million.

TABLE 6.IX Summary of Costs

	Millions
Material	$15.26
Labor at $10/hr	$4.57
Overhead at 85%	$3.88
SUB TOTAL	$23.71
Profit at 10% (arbitrary)	$2.37
Appended costs[1]	$0.50
Shipyard bill	$26.58 (say $26.6 M)

1. Appended costs include classification society fees and similar costs that the shipyard normally passes on to the owner without mark-up for profit. They also include tug and drydock charges based upon standard rates that already include profit. The figure used here is arbitrary and might well be omitted in preliminary design studies.

6.8.6 Estimating Overhead

What is meant by *overhead?* This division comprises all costs necessary to running the shipyard, but which cannot be associated with any particular ship under construction. Examples include salaries for administration staff and managers, cost estimators, and watchmen. Bills for electricity, real estate taxes, income taxes, and depreciation also are included.

Something else to note is that what is usually called *material* costs should more accurately be called costs for *outside goods and services.* Many shipyards, for example, use subcontractors to do the joiner work or the deck covering. Consulting service bills would come in this category, too.

Naval architects will seldom be called upon to delve into detailed estimates of overhead costs to be assigned to a ship being bid. They should, nevertheless, have some understanding of the difficulties involved. To begin with, there are two basic kinds of overhead, those that remain much the same regardless of how busy the yard may be: *fixed overhead,* and those that vary with the level of activity within the yard: *variable overhead.*

This leads to the conclusion that overhead costs taken as a percentage of labor costs (which is the usual estimating technique) will require a prediction of what other work may be under way in the yard while the proposed ship is being built. Clearly, these estimates are outside the naval architect's knowledge, but are the management's responsibility. It is enough to know that overhead costs, as a fraction of labor cost will drop if the yard is in a period of prosperity, with several contracts on hand.

6.8.7 Shipowner's Costs

The total invested cost of a ship is more than the shipyard bill (see Chapter 7 - Mission and Owner's Requirements). The shipowner has some appreciable costs of his own that would never arise had the ship not been built. Peter Swift (8) cited these figures for a large merchant ship built in 1978:

Spare parts	$600 000
Owner-furnished materials	$250 000
Plan approval	$1 000 000
Owner's supervision	$1 500 000
Administration & legal fees	$400 000
Total	$3750 000

On multiple ship orders some of these program costs can be distributed over the number of ships and are thus substantially lower on a per ship basis.

6.8.8 Duplicate Cost Savings

Some prospective shipowners ask shipyards to quote costs for building alternative numbers of identical ships. Such bidding is usually in the form of cost for one ship, or each of two, each of three, and so forth. Experience shows that unit costs go down as the number of identical units go up. Why should this be? There are two categories of reasons. The first is the matter of non-recurring costs. These are costs required to build the first ship but which need not be repeated for follow-on ships. Examples are engineering, plan approval, and preparation of numerical controls for fabrication. The second category consists primarily of labor learning: the increased efficiency workers acquire through repetitive work. There are also savings in material costs because suppliers, too, may experience savings.

The overall effect oflabor learning usually results in.cumulative average costs that decrease in a log-linear fashion. These are costs for each of so many units, *not* the cost of each additional unit. The general equation for the cumulative average cost (abbreviated $\overline{Y}$) is then

$$\overline{Y} = a / N^X$$

where

a = cost of the first unit
N = number of identical units
X = an exponent which will vary with the complexity of the ship and workers' experience.

A good many years ago it was concluded that a value of about 0.10 was appropriate for cargo ships built in American shipyards.

It is worth noting that with log-linear savings, the relative drop in cost remains the same every time the quantity is doubled. For example, if each of two ships costs 95% of the cost of one ship (first ship 100% and the second 90%), then the cost for each of four ships would be 95% of the cost for each of two.

6.9 OPERATING COSTS

6.9.1 Perspective

The aim in this section is to provide a basic understanding of the various components that go to make up the annual costs of operating a ship, including both voyage costs and daily costs. Unfortunately, there is no practical way to present a tidy handbook of actual quantitative values, but there are a number of useful references (11-14) that present some, but they quickly are outdated.

The breakdown of costs discussed represents standard accounting practice in the U.S. marine industry. Perhaps the first thing that should be said about these accounting practices is that they can be misleading. As an example, the maintenance and repair category includes only money paid to outside entities, usually repair yards. Maintenance or repairs carried out by the ship's crew are charged to wages; and materials used are charged to stores and supplies.

6.9.2 Schedule Analysis

In predicting operating costs a basic step is to project the times involved in a typical round trip voyage, sometimes called a *proforma voyage.* Typically, such an imaginary, representative voyage would include, in sequence, estimated times for proceeding down a river, through a harbor, and out into the open sea, perhaps some time in passing through a canal, then more time in the open sea, followed by time in speed-restricted waters of a harbor, time to unload cargo, time to shift to another pier, time to load cargo, and then perhaps a mirror image of all of the foregoing until a complete round trip is completed and the ship is once more loaded at the first port and ready to leave. Factored into this must be some reasonable allowances for port and canal queuing delays and speed losses in fog or heavy weather. Time may also be lost in taking on bunkers or pumping out holding tanks.

The total time for the proforma voyage, when divided into the estimated operating days per year (typically 350-360), will give the estimated total number of round trips per year, which need not be a whole number.

6.9.3 Other Applications of the Voyage Analysis

These scheduling calculations serve other purposes as well. In bulk ships where deadweight is critical, they are used to establish the weight of fuel that must be aboard when the ship reaches that point in its voyage where draft is most limited. In this phase of the work, one should give thought to the relative benefits of taking on bunkers for a round trip versus only enough for one leg. And one must of course add some prudent margin (often 20 or 25%) for bad weather or other kinds of delays.

The days per round trip estimate can also be used to establish the weight of other non-payload parts of total deadweight that are a function of days away from port: fresh water, stores, and supplies. Finally, all this may lead to that critical number: the annual cargo (or passenger) transport capacity. That estimate of actual annual transport achievement should be tempered by some realistic assumptions as to probable amounts available to be carried on each leg of the voyage. In the bulk trades, that might amount to 100% use one way, and return in ballast. In the liner trades, one might typically assume 85% full outbound, 45% inbound but this varies greatly depending on trade and route.

In more advanced studies the naval architect may need to make adjustments for minimum allowable freeboard changes brought on by geographic or seasonal requirements. Ice operations may also be a factor.

6.9.4 Voyage Costs

Voyage costs are those that are influenced primarily by the particular voyage in which the ship is engaged.

The biggest such expense is usually that for fuel although today lubricating oil costs are also significant. With the aid of the proforma voyage the naval architect is ready to make a voyage profile: a table showing for each segment the hours required, the horsepower required, the fuel rate per horsepower-hour (which is usually higher at reduced powers) and the resulting amount of fuel required. The total fuel needed for a single round trip can be derived from this information. Multiplying that by the round trips per year to yield the estimate for the annual main engine fuel requirement. Multiplying that number by the unit cost of fuel provides the estimated annual main engine fuel bill. This is also performed for lubricating oil.

Next, repeat the steaming profile exercise to come up with the annual costs for generator fuel. This step should be kept separate from the main engine estimate because the amounts required follow different patterns and perhaps, being a higher quality fuel, may have a higher unit price.

The other components of voyage costs (port and canal fees, tug service, pilotage fees) vary widely and are hard to generalize. Some port costs are on a per-use basis, others are on a per-day basis. Pier charges may be based on ship length. Pilotage may be based on draft. If one wants to relate these cumulative costs to a single parameter, Net Gross Tonnage could be used, but the cubic number might be as good as any.

Another important cost is that of cargo handling, which mayor may not be included in the contract, depending on the trade. If it were to be included it logically would be treated as a voyage cost. Associated with this may be brokerage fees and cargo damage claims, hold cleaning, dunnage, rain tents, and other miscellaneous cargo-related expenses. In some studies cargo handling costs will be the same for all alternatives, in which case they can be all but ignored.

6.9.5 Daily Costs

The other major family of operating costs comprises those that continue more or less year-round regardless of the voyage. Principal among these, usually, is that of crew wages and benefits. There was a time when crew numbers were closely related to hull size and horsepower. Now, however, with rational schemes for reducing personnel, crew complements are nearly independent of ship size and power. Numbers now usually vary between one and two dozen, depending on union agreements and shipowner's willingness to invest in automated equipment, more reliable components, and minimum-maintenance equipment (better coatings, for example).

In addition to direct daily wages there are many benefits paid to seafarers. In some instances there may be crew rotation schemes so that crew members are on year-round salary, with vacation times that may amount to as much as a day ashore for every day aboard. There are sick benefits, payroll taxes, and repatriation costs (travel between home and ship when rotating on or off). These are major increments that must not be overlooked.

For general studies, not specific to any owner, it is necessary to set up a wage and benefit equation that recognizes that total costs are not directly proportional to numbers because automation and other crew-reduction factors tend to eliminate people at the lower end ofthe pay scale. The general equation may take this form

$$\text{Annual cost of wages, benefits, etc.} = f_1(N_C)^{0.8} + f_2N_C$$

where NC = number in crew, and fJ and f_2 are coefficients that vary with time, flag, and labor contract.

The cost of victuals is a function of numbers of people aboard and operating days per year. Compared to wages, these costs are modest, and most owners consider the money well spent as a key element in attracting and retaining good seafarers.

The annual cost of hull and machinery insurance is based on the ship's insured value and size (underwriters use a Formula Deadweight, which is effectively the Cubic Number). A typical figure might be one percent of the first cost. First cost is a rather illogical basis for fixing insurance premiums, but the marine insurance business is marked with such irrational practices.

Protection and indemnity insurance (protecting the owner against law suits), usually based on Gross Tonnage of the shipowner's fleet, may add an annual cost of about 0.5% of the first cost. The two kinds of insurance costs are frequently lumped. Their annual cost, then, may be estimated as 1.5% of the first cost.

Annual costs for maintenance and repair (M&R) can be estimated in two parts. Hull M&R will be roughly proportional to the cubic number raised to the two-thirds power. Machinery M&R will be roughly proportional to the horsepower also raised to the two-thirds power. A refinement on this approach is embodied in the following approximation

$$\begin{aligned}\text{Annual cost of M\&R} &= f_3(LBD)^{0.685} + f_4MCR \\ &\quad + f_5(MCR)^{0.6} + K_1\end{aligned}$$

where MCR is main engine's maximum continuous rating in kW, n, f4, and f5 are coefficients that vary with kind of ship, owner's policies, and so forth, and KJ is a fixed amount regardless of hull size and engine power.

The annual cost of stores and supplies would consist of three parts. The first would be proportional to the ship's size (mooring lines for example). The second would be proportional to the horsepower (machinery replacement parts, for example). The third would be proportional to the number of crew members aboard (paint and cleaning compound, for examples).

A final daily cost category covers overhead and miscellaneous expenses. This would have to absorb a prorat~d share of the costs associated with maintaining one or more offices ashore. Shore staffs may number anywhere from what can be counted on one hand to bureaucracies bordering on civil service multitudes.

It was mentioned earlier that the conventions of accounting practices can be misleading and that true costs of maintenance and repairs may be considerably higher than shown in the books. Similarly, the division between voyage costs and daily costs, as defined by time charters, may also be misleading. Clearly, a voyage involving frequent round trips and lockages will increase repair costs, yet M&R is treated as a daily cost. Another example is the not inconsiderable cost of lubricating oil. That will surely be influenced by the hours of full-power operation (a function of voyages selected) and yet it is by tradition entered under stores and supplies, a daily expense.

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Chapter 7

Mission and Owner's Requirements

Mark R. Buetzow and Philip C. *Koenig*

7.1 INTRODUCTION

The specific technical requirements demanded by the mission and the shipowner must be identified early in the project to allow development of suitable vessel construction specifications. Similarly, many commercial issues must be considered before deciding the contractual arrangements in acquiring a vessel. This chapter broadly considers these perspectives and their impacts. Two Sections, 7.2 and 7.3, cover technical areas, while Sections 7.4 and 7.5 cover commercial requirements. In this way, a complete picture of the shipowner's pre-contract *requirements definition* activities is presented.

Volume II includes chapters on each of the major types of vessels, rigs, and craft. In these chapters information on individual requirements peculiar to the various vessel types will be found. In most cases, however, these requirements were not developed from a *clean sheet of paper.* Supporting the type-specific requirements is a foundation of principles and guidelines, which are generally applicable to any merchant shipowner's requirements formulation process. These principles and guidelines are the subject of this chapter.

The purpose of Section 7.2, *Top Level Mission Requirements,* is to introduce the technical and economic areas, which form the basic definition of the commercial ship ac-
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the technical requirements setting, process. Sub)ects co'J-ered include:

- outline of a typical new construction specification,
- cargo type and capacity,
- principal characteristics,
- additional port requirements,
- rules and regulations,
- service speed,
- endurance,
- design environmental conditions, and
- vessel design life.

A numerical example problem is worked through which illustrates the key issues involved in determining the economic speed for a new merchant vessel.

Section 7.3, *Other Owner's Technical Requirements,* provides a discussion of more detailed requirements in the areas of:

- propulsion plant,
- electrical plant,
- electronic navigational and radio equipment,
- automation,
- manning and accommodations,
- hull structure,
- quality standards, and
- maintenance and overhaul strategy.

Section 7.4, *Ownership and Operating Arrangements,* outlines major commercial requirements that are considered when entering into shipbuilding contract. Topics covered here are:

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- Clperating,ancl Cltnermanagement agreements, ami
- vessel financing.

Section 7.5, *Shipbuilding Contract Price and Total Project Cost,* provides discussion of project cost elements and their importance to the owner. Included in this section are sample:

- shipowners costs for acquiring a large commercial trading vessel, and
- list of typical *owner-furnished equipment* (OFE)

7.2 TOP-LEVELMISSION REQUIREMENTS

7.2.1 Overview

A thorough understanding of the key mission requirements is essential to the development of suitable contract specifications and more importantly, is the cornerstone to ultimately delivering a vessel, which will prove successful in service by fully meeting the owner's needs. Ascertaining the best overall approach to determining and satisfying those needs is the primary responsibility of the operational, technical, and financial experts on the staff of the shipowner. At appropriate stages of the ship acquisition project, these individuals are assisted as needed by independent naval architects and marine engineers, commercial consultants, financial institutions, classification societies, model basins, and others. Shipyard involvement and assistance can and should begin as early in the process as practical.

The shipowner's needs depend on the service that the vessel is intended to perform. Vessels are procured for three overall purposes: national defense, marine services, and marine transportation. For each of these three general ship categories, specific *requirements definition* considerations apply.

7.2.1.1 National defense

Warships are not built to earn a commercial return and therefore their requirements setting processes do not follow the principles and guidelines outlined in this chapter. Formulating the principles behind naval vessel requirements is a significantly different problem than the equivalent topic in the commercial sphere. In addition to technical and cost factors, warship procurement projects are subject to overriding considerations of geopolitics, national defense, and industrial policy. Therefore, in the case of naval ship acquisition, the project requirements setting process must be handled on a case-by-case basis. The reader is referred to Chapter 54 and 55 for information on naval vessel project requirements.

7.2.1.2 Marine services

The primary mission of many vessels is to provide marine services. Towing, dredging, icebreaking, fishing, harbor firefighting, rescue, oil drilling, oil production, and pollution clean up are a few examples of marine services for which special vessels are designed and built. For these vessels, a complete understanding of the services the vessel is to provide is necessary prior to specification development and contracting. For instance, a tugboat could be designed to provide one or more of the following services: ocean towing, harbor and river towing, ship mooring assist, ship escort, harbor firefighting, and pollution clean up. For each service intended, requirements must be developed. Most of the principles discussed in this chapter apply to vessels in the marine service industry.

7.2.1.3 Marine transportation

The overseas transportation of goods plays an important role in the global economy. Throughout history, incremental and step improvements in the technical efficiency of marine transportation have created economies that have enabled dramatic increases in trade and global economic development. Although this ship category encompasses a wide variety of ship types and designs, the basic techno-economic requirements of commercial marine transportation follow certain principles and guidelines that apply across trades. These principles and guidelines are the main subject of this chapter.

Ships built for marine transportation (marine commercial trading) carry a wide variety of raw materials, intermediate goods, and products (1,2). A fleet breakdown of merchant vessels greater than 1000 deadweight tonnes is given in Table 7.I (see Chapter 3-The Marine Industry).

Key impacts on vessel requirements due to its commercial mission are discussed below. The relative importance of the various elements will vary significantly depending on the type of vessel. At a high level, the key items are largely common across different types of ship projects and there are many elements that are investigated regardless of the ship's service. The intent of this section is to highlight the most significant general requirements and discuss their potential impact on the vessel and its specifications. These requirements are included in new construction specifications prior to signing a contract for the construction of the vessel. Table 7.II shows typical headings of a new construction specification for a commercial vessel in outline form.

7.2.2 Cargo Type and Cargo Capacity

The type(s) of cargo to be carried and the cargo carrying capacity are fundamental defining characteristics for most ship projects and are usually known at the outset. Cargo and cargo capacity largely determine the type, configuration and physical size of the vessel. Trade and port requirements often set limits on principal particulars, which impact the vessel's cargo capacity. Shore storage capacity may also pose a limit to the vessel's cargo capacity.

Commercial trading considerations can also be important in determining the vessel's cargo capacity. For exampIe, regional or international trading patterns will establish market demands for different sized vessels. Vessels smaller than those typically engaged in a particular trade will usually operate at a higher net cost per tonnes of cargo delivered. In a particular competitive trade, the shipowner's gross receipts per tonnes of cargo are set by the market conditions largely irrespective of vessel size. Therefore, the profit making potential of the vessel can be highly dependent on its capacity and the trades in which it is engaged.

In many cases it is desirable for the vessel to be able to carry multiple types or grades of cargoes. Depending on the trade and service, being able to carry different types or grades of cargo can significantly improve the vessel's flexibility, utilization rate, and profit potential. For example, if a different cargo can be carried on a back-haul voyage leg, the vessel will have the potential to avoid voyages in ballast, which generate no revenue. On the other hand, requiring a ship to have the ability to handle various cargoes Of cargo grades can result in serious compromises in design and cost increases. For instance, an ore-bulk-oil carrier can carry a wider variety of cargoes but will cost more to build and operate than a conventional oil tanker. If a container ship is to be capable of carrying both 40 foot and 45-foot containers, then some cost increase and some loss of cargo hold space utilization can be expected.

7.2.3 Principal Particulars

In many trades or services, restrictions are imposed on one or more principle particulars, which in turn strongly influ~ ences the vessel's design. These trade restrictions, and their resulting impacts on related aspects of the vessel's design,

TABLE 7.1 World Ocean Going Fleet Breakdown

Ship type category	*Number of ships*	*Percentage by number of ships*	*Deadweight tannes (millions)*	*Percentage by Deadweight tonnes*	*Gross Tons (millions)*	*Percentage by Gross Tons*	*Average age, years*
Bulk dry	5000	10.8	268.1	33.0	149.6	27.4	14
Crude oil tanker	1793	3.9	242.5	29.8	130.8	24.0	13
Container	2756	5.9	76.5	9.4	66.8	12.3	10
General cargo	16466	35.5	75.4	9.3	53.2	9.8	22
Oil products tanker	5191	11.2	41.6	5.1	25.2	4.6	22
Chemical	2598	5.6	30.4	3.7	18.6	3.4	14
Bulk dry/oil	201	0.4	14.5	1.8	8.3	1.5	17
Ro-ro cargo	1871	4.0	13.7	1.7	27.5	5.0	17
LPG tanker	1025	2.2	11.1	1.4	9.4	1.7	16
Other bulk dry	1104	2.4	9.1	1.1	6.8	1.2	18
LNG tanker	128	0.3	8.0	1.0	10.8	2.0	14
Refrigerated cargo	1407	3.0	7.3	0.9	6.9	1.3	19
Self-discharging bulk dry	171	0.4	5.7	0.7	3.3	0.6	26
Passenger/ro-ro cargo	2634	5.7	4.0	0.5	14.2	2.6	21
Other dry cargo	259	0.6	2.1	0.3	2.0	0.4	25
Passenger (cruise)	372	0.8	1.3	0.2	8.9	1.6	23
Other liquids	348	0.8	0.8	0.1	0.5	0.1	24
Passenger ships	2710	5.8	0.5	0.1	1.3	0.3	20
Passenger/general cargo	339	0.7	0.3	0.0	0.6	0.1	31
Total cargo carrying	46 373	100.0	812.9	100.0	544.9	100.0	19

Source: Lloyd's World Fleet Statistics 2001

TABLE 7.11 Outline of Typical New Construction Specifications for a Commmercial Vessel

Part 1: General Provisions	Part 2: Hull Specifications	Part 3: Machinery Specifications	Part 4: Electric Specifications
Intent	General particulars	Machinery particulars	Electric installation in general
Rules, regulations and certificates	Hull structure	Main engine	Cable installation
Material	Navigation equipment	Shafting and propeller	Electric generators
Buyer's supplies	Deck machinery	Steam generating plant	Transformers and batteries
Ship's form	Mooring outfit	Electric generating plant	Switchboards
Trim and stability	Masts and cargo gear	Pumps	Electric distribution
Determination of deadweight	Hatch covers, manholes, and doors	Oil purifiers	Motors and starters
Inspection and testing	Ladders, rails, elevator, etc.	Air compressors, fans, and air reservOIrs	Electric lighting
Trials and test at sea	Windows and scuttles	Heat exchangers	Electric interior
Vibration	Ventilation and air conditioning	Piping system in engine room	Communication equipment
Noise	Life saving appliances	Piping schedule	Electric nautical equipment
Plans	Firefighting system	Insulation and lagging	Radio equipment
Units	Hull piping	Miscellaneous equipment	Entertainment equipment
	Cargo handling system	Control and instrumentation	Performance monitoring system
	Refrigerated stores	Spare parts and tools	Spare parts and outfit
	Hull wooden work	General tools	
	Joiner work, deck covering, and insulation		
	Accommodation furnishing		
	Commissary outfit		
	Stores and lockers		
	Corrosion protection		
	Ship's identification, etc.		
	Spare parts and inventories		

need to be fully understood before a proper specification can be developed. Following is a brief discussion of common mission impacts on certain principle particulars.

Port limitations on maximum vessel draft commonly pose the most critical dimensional constraint for a vessel's design. This applies to a wide variety of vessels including river tugs, barges, ferries, naval vessels, cruise ships, tankers, and others. Draft restrictions in turn influence other aspects of the vessel's design such as length, beam, speed, propeller diameter, power, seakeeping and ultimately, construction cost and operating cost. The deeper a vessel's draft, the fewer ports it will be able to call at. Vessel trading flexibility, profit potential and resale value is thus impacted.

Limits on vessel length are set by berth restrictions at the ports the vessel is intended to serve. Beam may be limited by deep-water channel widths and canal widths. For example, ships transiting the Panama Canal are restricted to a maximum beam of 32.31 m. Cargo handling also imposes beam limits in some cases. Not all container terminals are able to load and unload large post-Panamax containerships because of the limited reach of their cranes. Similarly, the ship's depth can be limited by loading and offioading facilities at ports of call. Finally, air draft (extreme height of vessel above waterline) can be an important design limit due to bridge clearance restrictions. This can restrict the number of levels in the deckhouse and require the use of fold-down antennas.

TABLE 7.111 Vessel Design Requirements Commonly Impacted by Ports

Maximum displacement
Maximum cargo capacity
Maximum length overall
Maximum beam
Maximum draft
Maximum projected transverse sail area (for windage)
Maximum air draft
Minimum ballast capacity to meet freeboard requirements of port's cargo loading and unloading facilities
Shipboard cargo loading and unloading systems, arrangements, and locations
Mooring arrangement, number of winches, types and number of ropes and wires
Minimum length of flat-of-side
Ballast exchange capability
Maneuvering capability
Bunkering and lube oil transfer arrangements
Fresh water transfer arrangements
Storing arrangement
Sewage disposal
Engine room slop disposal
Garbage disposal
Engine exhaust emissions
Noise emissions
Odor emissions
On board oil spill containment and clean-up equipment (for tankers)
Cargo vapor recovery (for tankers)
Underkeel clearance in channels
RO-RO ramps

7.2.4 Other Port Requirements

Certain ports-of-call impose additional restrictions, besides limitations on principle particulars, that must be complied with. These requirements impacting the design and specifications of the vessel should be identified early in the design process and incorporated into the new construction specifications as appropriate.

For instance, the cargo loading/unloading arrangement of the vessel must be compatible with the cargo handling facilities at the port. Many docks require a minimum length of flat-of-side (flat area of side shell in midship region) at ballast and loaded drafts that permit proper berthing against dock fenders. Some ports have very specific requirements for the number, type, and location of mooring wires or ropes to be used for mooring. Enhanced maneuvering capability by use of thrusters may be necessary or commercially desirable in certain ports in order to minimize tug usage fees.

Environmental requirements are becoming increasingly strict. Emissions of noise and air pollutants (vapor, particulates) are coming under closer scrutiny and this is having a greater influence on ship requirements setting. Some ports require that all ballast taken on in other port locations be exchanged with ocean seawater to minimize port-to-port transfer of aquatic plant and animal life. In these cases, the vessel must be designed to allow this mid-ocean ballast water exchange. Table 7.III provides a checklist of common port issues affecting ship requirements.

7.2.5 Rules and Regulations

Chapter 8 presents a detailed discussion on Regulatory and Classification Requirements. A brief description is presented in this chapter in order to provide an understanding of the owner's considerations ofthis matter. Rules and regulations affecting ship project requirements are promulgated and enforced by the following types of bodies:

- the International Maritime Organization (IMO),
- the national government of the country in which the ship is to be registered (the flag state),
- the port state, and
- the classification society.

A vessel's flag of registry, its classification society, and the ports where it trades will establish the laws and regulations with which it must comply. For instance, a bulk carrier built to operate on the U.S./Canadian Great Lakes will be governed by a significantly different set of laws and regulations than a similarly sized vessel built to carry a similar cargo in unrestricted ocean-going service between ports in multiple countries.

The flag state (country in which a vessel is registered) determines the underlying laws and regulations that apply to a ship's design, construction, and operation. Most flag state technical and operational requirements originate from the country's enactment of global protocols adopted by the International Maritime Organization (IMO) of the United Nations. For certain subjects, IMO has established general guidelines but has delegated the determination of specific requirements to the classification societies. Furthermore, some countries including the United States and Canada have promulgated supplemental regulatory requirements that are more demanding than IMO regulations. In some instances these address areas not covered by IMO.

The classification society chosen by the vessel's owner can also impact the ship's design. Classification societies may stipulate requirements that exceed those of the flag state. Furthermore, classification rules are usually prescriptive, whereas IMO regulations tend to be more general. When this is the case, the specifics of an actual requirement are effectively delegated to the classification society or the flag state to establish within the intent of the general IMO guideline. Variations in interpretation on the part of the different flag states and classification societies makes it possible for vessels meeting different specific rule sets to all be in compliance with overarching international requirements.

Individual ports are controlled by port states (national, state, provincial, and/or local governments of ports) and in many cases their specific regulatory requirements impact vessel operation and design. Some port states enforce unilateral requirements on all ships, regardless of flag or class, which call at any of that country's ports. In some instances the requirements imposed by local governments are stricter yet than those of the national government of the port state. The United States is a prime example of a country having enacted such unilateral rules, ones that in some cases conflict with IMO requirements. At a minimum, port states randomly inspect vessels for compliance with international requirements and check for adequate onboard documentation covering classification, insurance, safe manning levels, data entry per certain IMO protocols, etc. Port State authorities also may detain ships for gross or dangerous infractions of international or class requirements (see Chapter 8 for a further discussion of Regulatory and Classification Requirements).

7.2.6 Service Speed

For marine trading vessels, optimum service speed is that which minimizes the overall cost of marine transportation. The analysis is carried out by studying how capital and operating costs change as the speed is varied. For a given trade, an increase in ship speed will:

- increase cargo delivered per unit time,
- decrease cargo inventory carrying cost,
- increase capital cost, and
- increase annual fuel cost.

7.2.6.1 Amount of cargo delivered per unittime

For a given ship, the amount of cargo delivered per unit time increases with speed, as the ship is able to complete more voyages (or fractions of voyages) per year. If all other factors are kept constant, a faster ship (able to complete more voyages per year) is more productive than the slower ship. If the throughput capability of the faster ship is considered to be the reference point, then for any slower ship, it will be necessary to obtain additional tonnage via acquisition or charter to make up for the loss of cargo throughput compared to the faster ship.

7.2.6.2 Cargo inventory carrying cost

In addition to delivering more cargo per unit time to the destination point, faster transit time reduces inventory-carrying costs. Between the loading port and the discharge port, each consignment of cargo is in storage on board the ship and is not being productively employed in its intended end use. The financial value of the cargo and the time it is onboard represents an opportunity cost, which is taken into account in the selection of the speed of the ship.

7.6.2.3 Capital cost

Faster ships usually incur higher capital costs due to their more complex hull form and powerful machinery plants.

7.6.2.4 Annual fuel cost

Once in service, annual fuel consumption and fuel cost will be higher for the faster ship due to the higher required horsepower.

Which of these four factors is dominant, depends on the trade. In trades involving high value cargoes (consumer goods, fresh foodstuffs) or vessels with high construction costs (LNG carriers), there is typically a wider range of assessed optimum speeds than found in trades in low value cargoes (grain, iron ore). The length of haul also has an effect on optimum speed. As the distance between ports of call decreases, the proportion of time the ship spends in port increases. If port time dominates, then the economic impact of at-sea fuel economy and vessel speed is reduced. Care should be exercised in specifying a speed markedly slower than usual. Vessels have long economic lives and *under speed* vessels will incur a penalty if they have to be sold for further use in a longer trade.

Other factors can have an overriding effect on the determination of optimum speed. Scheduling requirements drive vessel speed requirements in trades that place a premium on maintaining tight schedules (for example, LNG and container liner operations). Generous margins on service speed may be advisable in these cases in order to ensure that port or weather will not delay the overall voyage schedule. Some vessel types or vessel trading patterns may not have readily available alternative transportation options (LNG carriers, ice-strengthened vessels, and specialty vessels). In these cases vessel availability is a paramount consideration.

Consider an example optimum speed calculation. In this case, the shipowner is planning the acquisition of a 155 000 deadweight tonne tanker to operate in a 6000-mile one-way trade. The basic information is shown in Table 7.IV.

In this particular trade, the owner has found that most ships have service speeds in the neighborhood of 15 knots. Therefore, a range of speeds from 13 to 17 knots will be investigated. 13 knots will be taken as the baseline for the calculations.

As discussed above, within a given speed neighborhood there are four primary economic effects as speed is incrementally increased:

1. operational earnings due to increased amount of cargo delivered per unit time,
2. operational savings due to reduced cargo inventory carrying cost,
3. increased operational cost due to increased consumption of fuel, and
4. increased capital cost.

TABLE 7.IV Input Data for Optimum Speed Case Study

Vessel life	20 years
Operating days	355 days/year
Cargo per voyage	150 000 tonnes
Marginal freight value of additional cargo carried	\$8.98/tonne[1]
Fuel cost	\$100/tonne
Marginal cost of additional horsepower	\$800/bhp[2]
Average port fuel consumption	19.1 tonnes/day
Crude oil value	\$146/tonne
Time value of money	10%/year

1. This is the shipowner's cost of transporting incremental cargo by alternative means and is used in Table 7.V to calculate the savings realized by higher transportation throughput as speed is marginally increased. As speed increases, the ship's increased productivity will allow the owner to reduce his chartering expense-the owner can release a certain amount of chartered tonnage for each 1/2 knot increase in his own ship. The \$8.98 figure is calculated by the shipowner based on technical and market research. It includes the capital cost of the vessel assuming new construction. In this case it is based upon providing alternative transportation on a 15-knot vessel.
2. Includes the installed cost of the larger engine, longer engine room length, larger auxiliaries and increased fuel capacity. This constant *800IHP* is an approximation since this cost is a step function as increased horsepower results in increasing number of cylinders or engine size.

Maintenance costs do not have a significant impact in this example and are not considered.

An engineering economics analysis is performed to determine the optimum speed (3-6). For a detailed discussion on Engineering Economics see Chapter 6. Tables are developed to assess the various impacts at each half-knot increment within speed range (13 to 17 knots in this example). Then, the operational cash flows are combined into a net annual incremental operational savings. Finally, the internal rate of return (IRR) method is used to compare the initial capital expenditure of installing increased horsepower to the net annual incremental operational savings over the twenty year life of the ship. The calculations are shown in Tables 7.V through 7.VIII.

An increase in horsepower represents an investment, which must earn a positive return for the owner. In this example, each half-knot increment in speed has a decreasing IRR. The owner's optimum choice is, therefore, determined by a marginal analysis: speed is incrementally added until the point is reached where a further marginal speed increase results in an IRR which is less than the minimum acceptable rate of return. Figure 7.1 shows that for an owner with a 15% cost of capital, 15.5 knots is optimum speed for a 6000-mile one-way trade. For a 10% cost of capital, 16.7 knots is optimum.

Determining the cost of capital or minimum acceptable rate of return on investments in ship speed (or on investments in general) is discussed in standard texts on corporate finance (7) and engineering economics (8,9). Another complex issue is tax effect.

The example problem shown here does not account for tax considerations. These will vary from situation to situation and must be included in an actual business assessment. Complex tax situations are often created in merchant ship acquisition projects and tax issues must be taken into account.

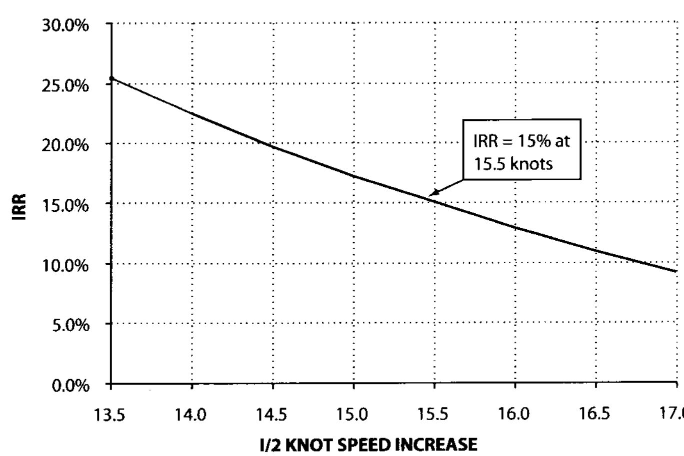

Figure 7.1 Internal Rate of Return for Incremental 1/2 Knot Speed

TABLE 7.V Annual Operational Savings Due to Increased Amount of Cargo Delivered Per Unit Time

1	2	3	4	5	6	7	8
Avg speed (knots)	*Round trip sea days*	*Port days per voyage*	*Total days per voyage*	*Voyages per year*	*Cargo per year, thousands of tonnes*[1]	*Cargo increase, each ½ knot*[2]	*Cargo savings/ ½ knot, $1000/yr*[2]
13.0	38.46	5.50	43.96	8.08	1211.3	—	—
13.5	37.04	5.50	42.54	8.35	1251.9	40.6	364.6
14.0	35.71	5.50	41.21	8.61	1292.0	40.2	361.0
14.5	34.48	5.50	39.98	8.88	1331.8	39.8	357.4
15.0	33.33	5.50	38.83	9.14	1371.2	39.4	353.8
15.5	32.26	5.50	37.76	9.40	1410.3	39.1	351.1
16.0	31.25	5.50	36.75	9.66	1449.0	38.7	347.5
16.5	30.30	5.50	35.80	9.92	1487.3	38.3	343.9
17.0	29.41	5.50	34.91	10.17	1525.3	38.0	341.2

1. Cargo per year = ship cargo capacity × voyages per year = 150 000 × Column 5.
2. Cargo savings for each ½ knot increment = cargo increase per half knot × market freight rate of additional cargo carried = Column 7 × $8.98 per tonne. The result represents the savings due to not having to move the incremental cargo by other chartered vessels.

TABLE 7.VI Annual Operational Savings Due to Reduced Cargo Inventory Carrying Cost

1	2	3	4	5	6	7	8
Avg speed (knots)	*Loaded sea days per vessel*[1]	*Cargo replacement tonnes (1000)*[2]	*Sea days req'd to move 1000 add'l tonnes*[3]	*Sea days req'd on in-chartered vessel*[4]	*Total sea days*[5]	*Sea days savings for ½ knot*	*Inventory savings for ½ knot $1000/yr*[6]
13.0	155.3	314.0	0.111	34.9	190.2	—	—
13.5	154.5	273.4	0.111	30.4	184.9	5.3	31.8
14.0	153.8	233.2	0.111	25.9	179.9	5.2	31.2
14.5	153.1	193.4	0.111	21.5	174.6	5.2	31.2
15.0	152.4	154.0	0.111	17.1	169.5	5.1	31.6
15.5	151.6	115.0	0.111	12.8	164.4	5.1	30.6
16.0	150.9	76.3	0.111	8.5	159.4	5.0	30.0
16.5	150.2	38.0	0.111	4.2	154.5	5.0	30.0
17.0	149.5	0.0	0.111	0.0	149.5	4.9	29.4

1. This column shows the number of days per year in which the ship is at sea with cargo on board. For the 17-knot case, there are 29.41 sea days per round trip (Table 7.V, column 2). Half these days are loaded; half are in ballast. There are 10.17 trips completed per year (Table 7.V, column 5). Therefore, days per year with cargo on board = loaded sea days per trip x trips per year = ½ (29.41) × 10.17 = 149.5. For the 16.5-knot case, we have ½ (30.30) × 9.92 = 150.2, and so on for the other speeds.
2. For each speed, this column shows the annual amount of cargo that needs to be made up by in-chartered tonnage to make up for each ½ knot speed decrease below 17 knots. The 17-knot case carries 1525.3 thousand tonnes per year (Table 7.V, column 6). The 16.5-knot case carries 1487.3 thousand tonnes per year (Table 7.V, column 6). The difference is the *cargo replacement tonnes*, 38.0 thousand tonnes.
3. This column shows the number of days at sea required on an assumed 15 knot in-chartered ship to handle the required make-up tonnage for each ½ knot speed decrease below 17 knots. The 15-knot ship does 152.4 loaded sea days/yr. (column 2) and 1.37 million tonnes cargo per year (Table 7.V, column 6). Sea days required to move 1000 tonnes of cargo on the in-chartered vessel = 152.4 / 1371.2 = 0.111
4. Sea days required on the in-chartered vessel = column 3 × column 4.
5. Total sea days = sea days on project vessel + in-chartered vessel = column 2 + column 5.
6. This column shows the annual finance charges saved due to sea days saved. Value of cargo = 150 000 tonnes × $146/tonne = $21 900 000. Time value of money = 10%. Finance charge for the cargo = ($21 900 000)(10%) / 365 = $6000 per day. Column 8 = ($6000/day) × column 7.

TABLE 7.VII Increased Annual Operational Cost Due to Increased Consumption of Fuel

1	*2*	*3*	*4*	*5*	*6*	*7*	*8*
Avg speed knots	*bhp*[1]	*Fuel at sea, tonnes per day*[1]	*Fuel at sea, tonnes per yr*	*Fuel in port, tonnes per yr*	*Fuel per year, tonnes*	*Fuel increase for ½ knot, tonnes/year*	*Cost of fuel incr. for ½ knot, $1000/year*
13.0	11 262	32.7	7167	848	11 015	—	—
13.5	12 612	36.7	11 131	877	12 208	1193	119.3
14.0	14 066	40.9	12 577	905	13 482	1274	127.4
14.5	15 627	45.4	13 907	933	14 840	1358	135.8
15.0	17 300	50.3	15 323	960	16 283	1444	144.4
15.5	19 089	55.5	16 828	988	17 815	1523	153.2
16.0	20 996	61.0	18 423	1015	19 437	1622	162.2
16.5	23 027	66.9	20 110	1042	21 152	1714	171.4
17.0	25 184	73.2	21 893	1068	22 961	1809	180.9

1. BHP and fuel consumption per day at sea verses speed are determined by engineering studies.

TABLE 7.VIII Internal Rate of Return (IRR)

1	*2*	*3*	*4*	*5*	*6*
Avg speed (knots)	*bhp*[1]	*bhp increase for ½ knot*	*Capital cost of bhp increase, $1000*[2]	*Net incremental operational savings, $1000/yr*[3]	*IRR for ½ knot speed increment*[4]
13.0	11 262	—	—	—	—
13.5	12 612	1350	1080.0	277.1	25.3%
14.0	14 066	1454	1163.1	264.8	22.4
14.5	15 627	1562	1249.2	252.8	19.7
15.0	17 300	1673	1338.4	240.0	17.2
15.5	19 089	1788	1430.7	228.5	15.0
16.0	20 996	1908	1526.0	215.3	12.9
16.5	23 027	2031	1624.4	202.5	10.9
17.0	25 184	2157	1725.9	189.7	9.1

1. BHP verses speed is determined by engineering studies.
2. Capital cost of BHP increase = BHP increase × $800/bhp from Table 7.IV.
3. Net incremental savings = savings due to cargo delivered (Table 7.V, column 8) + inventory savings (Table 7.VI, column 8) – increased fuel consumption (Table 7.VII, column 8).
4. Internal rate of return for one time capital cost increase (column 4) and 20 years of annual net incremental operational savings (column 5).

Benford, and Hurley and Johnson (5,10) give recent examples of how tax considerations can affect engineering economic analysis. There is an increasing use of Tonnage Taxes, such as introduced in the UK, which effectively means that trading operations are not taxed. Instead an annual Tonnage tax is applied depending on fleet size not profitability.

In the preceding example the owner knew the size of ship and wanted to determine the optimum speed. Many times the owner wants to know the optimum number, size and speed of ships to transport a given quantity of cargo from one port to another. Computer design synthesis programs are available to perform this number-crunching problem (see Chapter 13), and many more economic analyses have been published (11,12).

7.2.7 Endurance

The endurance is the distance the vessel can travel without refueling or replenishing stores. This design requirement must be established early enough in the project to ensure that adequate fuel oil capacity and provisions stores spaces can be provided. The required endurance is dependent on trade requirements and also on bunkering and storing strategies. On many long-haul trade routes, bunkers are less expensive at one end of the voyage than at the other. **It** can then prove advantageous to take on enough bunkers for the entire round trip at the more economical port. For such cases, the owner may require round-trip endurance.

When specifying the endurance, margins are usually included to ensure adequate fuel capacity in case of adverse weather or other circumstances that could increase fuel consumption. For instance, an endurance could be specified as 20000 nautical miles at a speed of 18 knots plus a 15% sea margin and an additional 4 days reserve. Fuel quality also is specified as this impacts fuel consumption.

7.2.8 Design Environmental Conditions

Proper consideration of environmental conditions in the design stage will ensure that the vessel is fully functional in its intended trade. Environmental conditions can impact many areas of the vessel's design. Operations in areas of high sea states suggests special consideration for:

- forebody and upper deck design, vessel lines and seakeeping model tests or studies,
- sea margins for propulsion power and service speed,
- personnel safety features, and
- structural loads and fatigue, which may warrant enhanced structural analyses, enhanced construction standards, and more conservative structural design criteria ..

Design ambient air and seawater temperatures influence features that maintain adequate habitability and operability levels. If the vessel will regularly operate in hot ambient conditions, the capacity and redundancy of the air conditioning and machinery cooling systems needs special consideration.

If the vessel will operate in arctic conditions, attention needs to be given to:

- steel material grades for ice belt structures, exposed shell, and main strength deck structures. Special grades of steel with higher toughness may be required for ships operating for long periods of time in low temperatures,
- stability reduction and weight accumulation from icing. Excessive icing can be especially hazardous to smaller vessels,
- forebody and upper deck design to minimize accumulation of freezing sea spray,
- insulation and heating systems for manned spaces,
- de-icing equipment such as steam lancing and hot water wash equipment. These systems are used to clear accumulated ice from mooring and other deck equipment,
- suitability of deck equipment for sub-freezing conditions and the need for equipment insulation or steam tracing, and
- protected work areas for personnel.

If the vessel must operate in ice-infested areas, structural ice strengthening and ice class notation from the classification society may be specified. Selection of most suitable design criteria and ice class notation is based on the region and associated ice conditions (first year ice, thickness and concentration of ice cover, multi-year ice) where the vessel will operate. The level of strengthening also will depend on whether the vessel is intended for independent navigation in ice or for navigation when escorted by an ice icebreaker or an ice strengthened vessel.

For further discussion on Ice-Capable Ships see Chapter 40.

7.2.9 Vessel Design Life

Establishing the design life of the new vessel will allow decision making on quality standards that can impact the actual economic life of the vessel. Higher standards for durability, and associated higher costs, can be justified if the vessel is expected to operate over a longer period of time. Ocean going international flag vessels are typically designed for a 20 to 25 year life but are operated for as short as 7 to 15 years. A prospective owner of a relatively expensive LNG carrier might opt for a 25-year life, especially if the owner has a long-term contract to supply LNG. For owners facing less certain long-term market demand, it is more difficult to economically justify the allocation of additional capital to build a longer lasting vessel.

Some key specification items that are typically impacted by the vessel's design life are the quality of coating systems, structural design standards, outfitting standards, and quality of machinery and equipment.

7.2.9.1 Quality of coating systems

This is especially important in ballast tank coatings. Future maintenance costs can be significantly minimized by up-front expenditures on:

- high quality coating materials,
- coating-friendly structural detail design,
- rigorous surface preparation, and
- extra care in the application of the coating system.

Investment in more durable coatings can lead to the realization of future cost savings in the form of:

1. lower cash outlays for coating maintenance, and
2. positive revenue gain due to reduced time required for repairs.

See Chapter 23 for a detailed discussion on Ship Preservation.

7.2.9.2 Structural design standards

If the vessel acquisition project calls for a long life vessel, then structural reliability considerations become increasingly critical. It is especially necessary to take account of the potential for fatigue failures in the ship's structure as it ages. It may prove necessary to specify increased corrosion margins, more extensive structural analysis, and improved structural details to ensure longer fatigue lives, as discussed in Chapter 21.

7.2.9.3 Outfitting standards

Higher quality outfitting standards may involve more durable design (see Chapter 22), lower maintenance requirements due to improved materials and reliable long-term after-sales support. For instance, more costly copper-nickel piping may be specified for engine room sea water systems, rather than less expensive but less durable galvanized piping. Use of extra heavy wall ballast piping and stainless steel fastenings on the upper deck are additional examples.

7.2.9.4 Quality of machinery and equipment

Quality factors here mirror those of non-machinery outfitting above. That is, more durable design, improved operability and lower maintenance requirements due to improved materials, and/or vendors that provide reliable long-term after-sales support. Selection of manufacturers and model types for onboard equipment can be highly impacted by the vessel's specified design life.

7.3 OTHER OWNER'S TECHNICAL REOUIREMENTS

7.3.1 Overview

The intended trade or service of the vessel, together with classification society and regulatory requirements, will in most cases largely determine the primary design requirements of the vessel. In addition, the shipowner will likely have additional technical requirements that are based on one or more of the following:

- safety,
- environmental protection,
- improved cost effectiveness (typically involving increased up-front capital expenditures that reduce future operating costs),
- operational needs (examples are fleet standardization, improved habitability, and ease of operation), and
- charterer's requirements.

The intent of this section is to highlight some common issues that are not necessarily requirements of the trade, classification society or regulations. Issues such as those discussed here will need to be resolved between the owner and the shipyard before contract specifications can be finalized.

7.3.2 Propulsion Plant

Capital cost, fuel consumption, reliability, type of service, and the owner's experience are usually key considerations when specifying the propulsion plant. The reader is referred to Chapter 24 for a more complete discussion of machinery.

7.3.2.1 Type of main propulsion plant

The majority of large ocean going ships utilize a single, low speed, diesel engine driving a fixed pitch propeller. There are many alternatives including medium speed diesel, gas turbine, steam turbine, and electric drives in single and multiple propeller configurations. Fuel efficiency and annual fuel cost are many times the governing influence in determining the type of propulsion plant for commercial trading vessels.

Passenger ships, naval vessels, and service type vessels, often have special requirements, driven by design constraints, such as severe volumetric limitations or operational needs for special machinery performance characteristics. For example, extremely quick machinery responsiveness, additional redundancy, and high electrical load requirements). These special requirements can drive the selection of an alternative type of propulsion plant.

7.3.2.2 Auxiliary systems design and automation strategy

The level of redundancy and sizing of auxiliary equipment such as HVAC units, fresh water generators, boilers, pumps, heaters/coolers, control & monitoring systems, and fuel treatment equipment reflects systems design principles and specific owner preferences based largely on in-service experience. Equipment and level of automation are chosen to fit the experience of the operators and level of manning.

7.3.2.3 Fuel quality

Outfitting the machinery plant to handle lower quality fuel increases capital cost but may also reduce annual operating costs and increase operational availability due to cheaper fuel and increased flexibility regarding the location where bunkers are purchased. Therefore, to select the fuel type, it is necessary to perform a trade-off analysis, such as that presented in Chapter 4.

7.3.3 Electrical Plant

The major electric plant issues to be considered include electrical power source, the level of redundancy, fuel quality, allowance for growth, and generator sizes. The reader is referred to Chapter 24 for a more complete discussion of electrical plants.

7.3.3.1 Prime mover

Alternatives for supply of electric power typically include high or medium speed diesel generators, steam turbine driven generators, and propulsion shaft driven generators. The type of propulsion plant, electric demands at sea and in port, and fuel consumption will be critical factors in deciding on an electric plant.

7.3.3.2 level of redundancy

Component and system redundancy should be specified in the context of a complete analysis of the ship system of which it is a part. Redundancy is a means, not an end and if the goal of total ship reliability can be achieved through improved systems design then costly redundancy can be minimized.

An important electrical plant decision is to determine how many generators are required in reserve, consideting in port and at sea electric power demands. For instanae, if one diesel generator is out of commission due to maintenance, should the vessel be fully operational if one more generator were to fail? In addition, switchboards, motors and circuits may have to be duplicated if the loss of their function cannot be tolerated.

7.3.3.3 Fuel quality

Although more costly initially, most medium speed engines can operate on the same lower cost heavy fuel as the slow speed engines typically used for the main propulsion plant. However, infrequent power requirements, lower emissions, and longer frequency between routine maintenance may dictate that a higher-grade fuel oil be used.

7.3.3.4 Allowance for growth

Some allowance for growth in electric power demand is usually provided because it can be very expensive to install incremental electrical power capacity after construction. Some electric demand increase can generally be expected over the life of the vessel.

7.3.3.5 Generator sizes

Generators of particular or differing sizes might be required to operate efficiently under all the modes of operation the vessel will commonly meet (at sea, in port, maneuvering, cargo handling, etc.). For example, the owner may not want large capacity units operating in low load condition for extended periods.

7.3.4 Electronic Navigational and Radio Equipment

Beyond the basic navigational and radio equipment required by regulation, there is a wide range of electronic navigational and radio equipment installed according to owner preference.

7.3.4.1 Redundant equipment

Electronic equipment needs frequent servicing. Often it is better to have a spare unit on board rather than depending on shore-side service people to be available where and when it breaks down.

7.3.4.2 Extra communications equipment

Special equipment is often installed for electronic data exchange, access to head office, in-port communications, crew's messages to home, etc. Recently the U.S. Navy has provided Internet service onboard many of its surface ships, so that the crew can participate in distance learning courses while at sea.

7.3.4.3 Equipment for navigational safety

Operators of ships involved in high speed, close quarters maneuvering, or carrying hazardous cargoes usually install additional navigational equipment, often complete integrated navigation systems which put all information and controls in the reach of a single operator similar to an aircraft cockpit. This is partly driven by the desire for one-man bridge operation.

7.3.4.4 Equipment for manning reduction

Reduced manning can be achieved by equipping the vessel with redundant radio equipment, automatic steering systems, integrated navigation systems, etc. Classification societies issue special notations, such as *one-man watch* to certify that the vessel is safe to operate at a reduced manning level.

7.3.5 Automation

Automation ordinarily is added when justified by increased safety or a reduction in manning, overtime costs~ or shoreside maintenance costs. Various levels of automation may be specified in conjunction with a vessel's classification, such as bridge control, unmanned engine room, dynamic positioning, etc. On a smaller scale, individual systems or items of machinery generally have various levels of automation available as options. Since the advent of the microprocessor, such options have become more widespread and cheaper.

7.3.6 Manning and Accommodations

Determining the accommodation requirements requires close coordination with the shipowner's operating organization. These requirements are influenced by manning levels, crew nationalities, level of standards, and visitor needs (such as for port officials, temporary maintenance crews, home office visitors, cadets in training). The primary accommodation issues include:

- number of cabins,
- accommodation and outfitting standards,
- type of cabin classes,
- public spaces,
- messing facilities,
- galley and provision stores,
- arrangement for ship's offices,
- storage spaces,
- sanitary facilities,
- laundries, and
- arrangement of control spaces.

7.3.6.1 Number of cabins

Once the crew size has been determined, it is necessary to decide the number of cabins. This will depend on whether single or multiple occupancy is required. Single cabins are almost universal on ocean going ships today. Thus, the owner's input will be necessary to establish the cabin count. The number of cabins will be dependent on factors mentioned previously.

7.3.6.2 Accommodation outfitting standards

Crew motivation and morale can be positively or adversely affected by accommodation standards. Important factors include the size of spaces, quality and type of furniture, flooring material, and size and layout of windows. In times of crew shortages and competition for proficient crews, higher standards may be advantageous. Accommodations should be as noise and vibration free as possible. IMO standards exist for acceptable levels of noise and vibrations in each type of accommodation spaces.

7.3.6.3 Type of cabins classes

For large commercial, ocean going vessels, there are a variety of classes of cabins, such as captain class, senior officer class, junior officer class, petty officer class, ratings class and dormitory. Each cabin class will have its own standard for room size, layout, and furnishing. For instance, captain and senior officer cabins typically have both a day room and a bedroom. Depending of the composition and nationality of the crew, traditional practice might be to separate the licensed officers from unlicensed crewmembers. Although the modem trend is toward more integrated accommodations (such as containerships which can in certain cases sail with crews of less than a dozen) the cultural makeup of the crew could dictate a certain degree of differentiation. For smaller service type craft, the cabin requirements and crew makeup are usually considerably simplified. Although there are national regulations for minimum cabin areas and other accommodation requirements, such as number of toilets per crew number, they are generally exceeded today.

7.3.6.4 Public spaces

The type of service and duration of voyage will largely influence the requirement for public spaces such as lounge, exercise room, library, swimming pool, and sauna.

7.3.6.5 Messing facilities

Depending on the size and composition of the crew, one or two mess rooms may be required for large commercial vessels. As in the case of accommodation, social practice on board ship could call for separate mess rooms for licensed and unlicensed crewmembers. For vessels that are inherently dirty, it is a good idea to provide one or more duty messes so that the crew may have mid-day meals or coffee breaks without the need to change from work clothes or coveralls.

7.3.6.6 Galley and provision stores

Galley facilities are tailored to the size and national composition of the crew and duration of voyages. Provision stores are best located on the same deck as the galley. When this is not possible, provisions lifts (dumbwaiters) are provided. Provision stores are sized appropriately with respect to the size of the crew and duration of voyages. Because ships are making increasing use of pre-packaged foods, ample storage shelf space should be provided.

7.3.6.7 Arrangement for ships offices

Offices on board should be tailored to the service of the vessel and type of operation. Typically, offices are provided for the senior officers. Current practice is to locate these offices away from the quarters. As part of any office complex, careful thought should be given to storage of ship's plans and reference materials. Modem offices include computer workstations and vessel-wide local area networks. A conference room may also be provided with adequate tables, seating and file storage.

7.3.6.8 Storage spaces

Typically storage spaces within the accommodations are at a premium and should be described in the contract specifications. They are provided for crew baggage, linen lockers, consumable stores, paint locker, etc.

7.3.6.9 Sanitary facilities

In large commercial vessels, crewmembers are typically provided with single cabins with private toilets and showers. This practice is not always followed in vessels where accommodation space is limited such as in smaller service type vessels or in vessels with large crews. IMO regulations restrict the discharge of liquid and solid wastes and certain port states have their own requirements. Accordingly, care is needed when specifying sewage retention, treatment and disposal facilities. For disposition of solid wastes, off-loading ashore may be suitable for short voyages, however for longer voyages trash and waste oil incinerators are commonly specified.

7.3.6.10 laundries

For most ocean going vessels, laundry facilities are required. Typically, heavy duty, industrial type laundry machines and dryers should be provided for washing bed linens and tablecloths. For personal laundry, separate facilities should be provided for officers and for ratings.

7.3.6.11 Arrangement of control spaces

Control spaces should suit the type of vessel and nature of the service. Typically good visibility of the control boards and operating areas should be provided. A convenient workstation design with office type furniture and computer stations should be considered. Control rooms typically require frequent consultation of instruction manuals and operating procedures. For these, ample storage shelves and cabinets should be provided, although today many drawings and manuals are being replaced by computers and information databases.

7.3.7 Hull Structure

Classification society rules are very prescriptive regarding hull scantlings. However, enhanced structural requirements may be appropriate based on environmental conditions of the intended trade, past experience, reliability expectations, and maintenance philosophy. Common enhancements include advanced structural analyses, limiting the use of high tensile steel in the hull structure, increased scantlings, increased corrosion margins, special quality coatings, improved structural details, and improved accessibility.

7.3.7.1 Advanced structural analyses

The owner may opt to specify additional structural analyses such as finite element, fatigue, vibration and dynamic load calculations to identify and correct structural weaknesses. As a result of these structural analyses, critical areas can be identified and special attention be given to them during fabrication and inspection during the vessel life. This can be an effective approach to minimizing the life-cycle cost of the vessel.

7.3.7.2 Limiting the extent of high tensile steel used in the hull

Unless otherwise constrained by the specifications, shipyards will often make extensive use of high tensile steel to design a more efficient structure, resulting in reduced light ship weight and correspondingly reduced construction cost. Although this approach can be effective, high tensile steel can be more susceptible to fatigue failures. Also, lighter scantlings associated with high tensile steel directly affect structural flexibility and buckling strength, which need to be carefully evaluated during design. Therefore, more intensive effort in structural design analysis may be appropriate if high tensile steel is used extensively.

7.3.7.3 Increased scantlings

Base on prior experience, some owners require that the scantling thickness be increased over that required by the classification societies.

7.3.7.4 Increased corrosion margins

Depending on the expected life of the vessel and the service, it may be worthwhile to specify corrosion margins over and above those required by the classification societies.

7.3.7.5 Specific structural enhancements

More severe design criteria (such as longer fatigue life), more stringent construction tolerances, or more robust structural details can be specified for historically troublesome structural details. Typical areas given consideration are hatch corners, web frame longitudinal cut outs, chocks, brackets, etc.

7.3.7.6 Improved access

Structural arrangements can be provided that allow improved access for inspection and maintenance of all structural areas and also allow removal of injured personnel carried on a stretcher.

7.3.8 Quality Standards

The shipowner often will find it necessary to require higher quality standards than those initially offered by the shipyard, required by regulations, or required by classification rules. Quality standards impact many aspects of the vessel, some of which are discussed below.

7.3.8.1 Safety standards

Providing a safe working environment is a key element in proper ship management. There are many opportunities for applying improved safety standards throughout the vessel and they are discussed in Chapter 16. For instance, improved emergency escape access for enclosed spaces such as ballast tanks and machinery spaces can be provided. Railings, gratings, and ladders of improved design can be specified and non-skid coatings can be used in high traffic areas. Additional or improved lifesaving equipment can also be provided. Firefighting systems can be enhanced by providing additional water spray systems, fire hydrants, and fire detectors. Specific noise and vibration standards can also be required to enhance habitability and safety.

7.3.8.2 Environmental standards

The shipowner may choose to build his vessel to higher environmental standards than required by rules and regulations. Examples include using environmentally friendly coatings, systems to reduce engine stack emissions, and cargo vapor recovery systems for oil tankers. Bunker tanks can also be located away from the vessel's side shell to reduce risk of oil spill in the case of a collision or side shell crack.

7.3.8.3 Construction standards

Fabrication deviation limits in most shipbuilding standards are based on the shipbuilding state of the art of the late 1960s. The applicability of these standards to modern ships built with higher tensile steel is questionable. A more stringent standard may be required by the shipowner for critical and highly stressed areas of the hull.

7.3.8.4 Regulatory standards

Especially in the case of international maritime regulations, it can take several years for new regulations to become finalized and effective. When contracting and constructing new vessels, the owner should consider requiring compliance with anticipated regulations not yet implemented, but that will be in force before a certain date or stage of construction.

7.3.9 Maintenance and Overhaul Strategy

Incorporation of the owner's maintenance strategies and philosophy into the design of the vessel will allow the owner to operate and maintain the vessel as intended. Some key maintenance issues that can affect the design include:

7.3.9.1 Maintenance while operating or when shutdown

Maintenance of auxiliary equipment during normal operations may require additional redundant equipment to allow operations to continue. For example, the number of auxiliary generators may be impacted if maintenance of these units will take place while the vessel is operating.

7.3.9.2 Riding crews

If maintenance work will be carried out periodically by special riding crews, then sufficient additional accommodations must be incorporated into the design. Tools and equipment such as air compressors and blasting equipment for paint work, or specialized tools for machinery work, must be provided to handle jobs for which the riding crews are not expected to bring their own equipment.

7.3.9.3 Spare parts in excess of classification society requirements

If these are to be supplied by the shipyard, they must be fully described in the specification. The quantity of spares to be provided can be influenced by remoteness of the ports of call, availability of parts and service, reliability requirements and criticality of service.

7.3.9.4 Spare parts stowage

The spare parts philosophy will impact onboard storing space needs. Certain spare parts must be carried on board; others may be stored in strategic locations ashore. For many spare parts, a complete set is needed for each ship. If the owner's fleet includes multiple ships sharing either a common total design or common design elements, then there are potential economies that can be realized by jointly sharing certain major spare parts with other vessels in the owner's fleet. This last strategy often is used for spare parts, which are expensive, and cumbersome yet infrequently needed (propellers, tail shafts, and anchors are typical examples).

7.3.9.5 Overhaul location

Sailing a vessel in ballast to a location remote from its trade route is costly because the ship incurs full operating costs while making the trip, but earns no revenue. Because of the high cost of such repositioning voyages, the trade or area that the vessel operates in restricts the location of shipyards that can be effectively used for dry-docking and periodic overhaul. These repair facilities can pose limitations on maximum beam, maximum length-over-all, and maximum draft in docking condition.

7.3.9.6 Overhaul frequency

The normal frequency of overhaul and dry-docking is dictated by classification requirements and can impact certain key elements of the vessel. For instance, if the vessel will be drydocked very infrequently, such as every five years, then anti-fouling bottom coating must be specified that is suitable for five years duration. Also in this case, the classification society may require interim underwater surveys for which special location markings are required on the outer hull to enable survey divers to determine their location.

7.4 OWNERSHIP AND OPERATING AGREEMENTS

7.4.1 Overview

Sections 7.2 and 7.3 consider typical technical requirements that must be understood and specified prior to contracting and constructing a vessel. The intent of this section is to provide background information on common critical commercial requirements that must be resolved before, during, and after contracting for the construction of a vessel. These issues are typically incorporated into commercial agreements such as charter party contracts and vessel management agreements (13). Besides those discussed below, there are many other commercial and legal issues, which can be important depending on the particular nature of the contracting arrangements and situation (14,15). In this context it is assumed that shipping is *afor profit* business subjected to competitive market forces. The following discussion, therefore, precludes such important shipping activities as military support, subsidized research & development, and other government-regulated shipping (such as those activities falling under local cabotage rules), as these do not operate in any sort of traditional *commercial* sphere. In particular, there are major commercial issues involving ship ownership arrangements, operating and other management arrangements, and vessel financing should a long-term commitment or outright purchase be appropriate. These issues are discussed in turn in the next three sections.

7.4.2 Tonnage Acquisition Alternatives

Chapter 4 discusses ship acquisition strategy. The following discussion builds on Chapter 4. Several standard forms of ownership arrangements have developed in the long history of maritime trade. In the context considered here, *ownership* is meant to be synonymous with *tonnage acquisition* of any sort. That is, *acquisition* should be interpreted to cover the gamut of how one might *acquire tonnage to move cargo (including passengers)for profit* whether it be an outright long-term acquisition via purchase of a ship at the one extreme or acquiring tonnage for a single voyage via a spot charter arrangement at the other extreme. Within this range, several new approaches have developed in recent years (such as freight service agreements and strategic bareboat charters) to address ever-changing requirements by both shipowners and charterers. Table 7.IX summarizes some key elements of *Tonnage Acquisition Alternatives,* spanning the spectrum from shorter-termllower control modes like spot charters through to the longer-termlhigher control modes represented by bareboat charters and outright purchases. This is by no means all-inclusive, as different segments of the maritime industry have developed many different products to meet the needs of both owners and charterers. Key questions in deciding what the right arrangement is for any given situation are:

7.4.2.1 Term of commitment

Is a short-, medium-, or long-term commitment to tonnage the most appropriate? The answer depends on several factors; among them being the duration of vessel need, one's outlook on the market, and the availability of tonnage under the various alternatives. An economic evaluation of the various alternatives against a market expectation can form the

TABLE 7.IX Tonnage Acquisition Alternatives

	Acquisition Mode			*Operating Costs*				
	General	*Specific*	*Typical Term*	*Capital*[1]	*Fixed*[2]	*Variable*[3]	*Freight Revenue*	*Key Features*
Short- to Medium-Term (Lower Control) Commitments	Spot (or Voyage) Charter	—	Single Voyage	Owner	Owner's Account	Owner's Account	\$/MT or lump sum	• Covers a contractually-specified voyage or range of voyage options • Begins at a load port at a contractually-specified time • Ends at a discharge port at the completion of the voyage
	Consecutive Voyage Charter	—	A series of single voyages	Owner	Owner's Account	Owner's Account	\$/MT or lump sum	• Same as a single voyage, but followed in direct continuation by a contractually-specified series of additional voyages
	Freight Service Agreement	—	Evergreen	Owner	Owner's Account	Owner's Account	\$/MT or lump sum	• A looser form of voyage charter agreement whereby an owner has first right of refusal to provide tonnage for a given voyage; if unable or unwilling to provide tonnage under the agreement, then the charterer is free to follow other alternatives
	Contract of Affreightment	—	6 months to 5 years	Owner	Owner's Account	Owner's Account	\$/MT or lump sum	• A commitment by charterer to move a given volume of cargo in a given period of time • Owner to make tonnage available against contractually-specified parcels, voyages, schedules, etc
	Time Charter	Short- to Medium-Term	1 month to 10 years	Owner	Owner's Account	Charterer's Account	\$/Day	• Similar to a consecutive voyage charter, but provides the charterer more flexibility for worldwide trading
Longer-Term (Higher Control) Commitment	Time Charter	Long-term (or Full Payout)	11–25 years	Owner	Owner's Account	Charterer's Account	\$/Day	• Similar to a consecutive voyage charter, but provides the charterer more flexibility for worldwide trading
	Bareboat Charter	Short- to Medium-Term	1–10 years	Owner or Lender	Charterer's Account	Charterer's Account	\$/Day	• Essentially a short-term (*operating* or true) lease of the ship, with fixed & variable operating costs for the charterer's account
	Bareboat Charter	Strategic	7–11 years	Owner or Lender	Charterer's Account	Charterer's Account	\$/Day	• A modification of a medium-term bareboat whereby the charterer has one or more options to terminate the charter after the initial fixed term & in doing so sheds residual value risk back to the owner
	Bareboat Charter	Full Term (or Full Payout)	20–25 years	Owner or Lender	Charterer's Account	Charterer's Account	\$/Day	• Essentially a full-term or full payout (*capitalized* or *finance*) lease of the vessel
	Outright Purchase	New building	Full life of vessel or until sold	Owner	Owner's Account	Owner's Account	N/A	• The owner may use the ship for his own account or arrange for any of the aforementioned contractual arrangements with the charter market
	Outright Purchase	Secondhand	Remaining life of vessel or until resold	Owner	Owner's Account	Owner's Account	N/A	• Similar to the outright purchase of a newbuilding except it's used tonnage • Introduces the ability for *asset plays* or *commodity trading* of tonnage by speculators in the market • Also note the *hedged asset trader*, a speculator who acquires secondhand tonnage for the purpose of *asset plays*, but is backed by a short-term charter to provide a known cash flow in the near-term

1. Capital Costs: Includes the purchase (contract) price, capitalized interest during construction (if any), depreciation tax credits which accrue from the acquisition, net of any residual value which the owner receives at the end of the acquisition.
2. Fixed Operating Costs: Includes seagoing labor, consumables such as ship stores, maintenance & repair costs including periodic overhauls & positioning, insurance, an allocation of shoreside (home office) overhead, and other miscellaneous fixed operating costs.
3. Variable Operating Costs: Consists primarily of port and fuel cost, but may also include costs to transit the Panama or Suez Canals, lightering costs at the load and/or discharge ports, and other miscellaneous variable costs specific to the voyage at hand.
4. Freight Revenue: Generally set by the market and therefore subject to the usual competitive forces & volatility of the market. To the extent that market forces allow it, freight revenue will be such that providers of tonnage recover their operating costs, can service their capital costs, and earn a profit commensurate with the risk of their business. In an unhealthy market, however, revenue may not allow a return on investment and may not cover some or all of one's fixed operating costs. But a floor on revenue will always exist at a level to cover variable operating costs, below which owners will sell, lay up, or otherwise idle their tonnage. And of course, to the extent that entry into a given shipping activity is relatively easy, unregulated, and/or inexpensive, an effective ceiling on revenue will develop as unusually high profits will attract additional market players, thereby increasing the supply of tonnage and drawing down freight rates (unless the demand for tonnage otherwise grows alongside the supply of tonnage).

basis for beginning to address this question. A large fleet may include vessels comprising many different terms of commitment.

7.4.2.2 Depth of commitment

Is it enough to have a call on a pool of tonnage under, for example, a freight service agreement or a contract of affreightment, or is a deeper commitment to a specific ship or a specific owner more appropriate? Among many factors, the answer depends on one's valuation of long-term (ongoing) business relations and their role in contributing to a venture's success and the ability to manage operational risk across pooled ships verses specific ships. A large fleet may include varying depths of commitment to different ships.

7.4.2.3 Degree of operational control

Is control of the deployment of the ship adequate to meet the need? If so, then a consecutive voyage charter or a short-term time charter may be best. If control over on board operations is needed, then a bareboat charter or outright purchase might be more appropriate. This is largely a risk management issue with the added consideration of strategic value (if any) arising from controlling the operations in-house vs. outsourcing them to an independent third party. Once again, a large fleet may consist of varying degrees of operational control across the ships in the fleet.

7.4.2.4 level of market exposure

Is exposure to shorter-term spot market volatility acceptable or is it more desirable to lock in a longer-term (perhaps fixed) freight component via term charter arrangements? This is first and foremost a business decision. Does one have a view on the market and is one willing to take a position in that market? Or is it sufficient to pay no more or no less than *market* on the assumption that that's what the incremental competitor is paying? Of perhaps secondary importance are questions such as: does one have other market -based cash flows in his/her business portfolio, which can act as a natural hedge against marine freight rate volatility? And does exposure to at least some portion of the market allow one to attract equity financing which he/she might not otherwise be able to attract? Finally, is one willing to take on medium-term spot market exposure in an acquisition vehicle like a strategic bareboat, which allows himlher to shed residual value risk back to the market at a later date in the charter? These are all key issues for any asset management strategy built on long-lived commodities such as ships.

7.4.3 Operating and Other Management Agreements

Once a mode of acquisition is decided (or mixed modt:s for a large integrated fleet of ships), an owner (again d¢fined in the broadest sense) faces decisions regarding operating agreements and other management agreements (e.g., commercial management and technical management). For the purposes of this discussion, these may be generically categorized as follows:

7.4.3.1 Operational management

Entails day-to-day running of the ships, including bunkering, port activities, voyage orders, manning, insurance, ship stores, etc. Includes operational administration of any contractual obligations accruing to the owner.

7.4.3.2 Technical management

Really a subset of operational management, but more focused on technical engineering and maritime expertise, such as new construction supervision, vessel conversions, maintenance and repair, upgrades and retrofits, emergency response, etc.

7.4.3.3 Commercial management

Arranges for commercial employment for the ships, seeking to maximize daily return, vessel time or space utilization, or some other commercial or financial measure of merit. In most cases also handles accounts payable and receivable, as well as commercial claims like demurrage, cargo contamination or loss, insurance claims, etc. Includes commercial administration of any contractual obligations accruing to the owner. Several alternatives readily present themselves:

- in-house management,
- one-off subcontracts for specific management elements,
- ongoing outside management by a third party specialist, and
- any mixture of these alternatives across the entire spectrum of ship management activities.

There are several issues that drive an owner to one or more form of management agreement. Most have to do with project control and risk management.

The basic issue is to determine an appropriate degree of operational, technical, and commercial control. This usually comes down to a risk management decision, vis a vis how much hands-on control of the various aspects of ship management is necessary to manage the risk and exposure from a mishap. Additionally, a shipowner must address the degree to which more or less control of the various aspects of vessel management provide strategic value to the company or venture at hand. That is, how much control is one willing to divest to *the outside* and how much does one want to retain *in-house* and out of the hands of outsiders or competitors?

Very closely allied to this issue is quality assurance. To what extent does one feel that in-house management provides higher quality service than does outsourcing one or more vessel management activities? Larger integrated firms may very well answer this question differently than smaller niche or specialized owner/operators. No discussion of control and quality assurance would be complete without mentioning the "vetting" process by which one assesses the quality of third party shipping assets and vessel management. An inspection program, whether in-house or third party, may be used to assess the vessel, its hardware, and its crew and onboard operations. A shore-side assessment program may also be in place for assessing the quality of home office management and quality control systems.

Figure 7.2 summarizes in qualitative fashion the relative levels of exposure to risk associated with different modes of tonnage acquisition.

7.4.4 Vessel Financing

Whether buying a ship outright or chartering it in some fashion from another owner, a ship must eventually be built. At the risk of stating the obvious, *without the cash,. there is no ship.* Raising the cash (financing the project) is therefore a very, if not the most, important step in a successful newbuilding project. In the classical sense, any long-term acquisition of tonnage should be justified on the basis of an outright purchase compared to the spot market. In this regard, many analytical techniques are available to help an owner in coming to a decision: discounted cash flow (DCF) analysis, including net present value (NPV) and rates of return (ROR), or internal rate of return, (IRR), as well as the probabilistic techniques wrapped up in decision and risk analysis (D&RA). Assuming that these economics favor acquisition, then a prudent owner will always look at taking advantage of the lowest cost of finance balanced against any perceived benefits from taking on other higher cost finance alternatives. The basic factors in the decision are:

- asset management and long-term forecasts,
- equity verses debt financing,
- weighted average cost of capital vs. debt rate,
- credit ratings and the cost of finance,
- leveraging off project credit or joint venture partner credit,
- private verses public financing,
- shipbuilder financing,
- discount rates,
- lease vs. purchase (equivalent interest rate of a lease),
- inflation rates,
- foreign exchange rates, and
- tax effects.

These issues are reviewed in the following paragraphs. For more detailed information, see Chapter 6 and any of the standard texts referenced throughout this chapter may be consulted.

7.4.4.1 Asset management and long-term forecasts

Decisions around long-term asset management necessitate the use oflong-term forecasts, both on the operating cost and freight revenue sides of the equation. This is because long-lived assets such as ships require large amounts of capital to build and/or acquire. The owner will only put such capital into ships if he believes that long-term revenues will exceed costs including a return on capital employed. This is very difficult due to the fluctuating ship demand.

7.4.4.2 Equity vs. debt

In general, cash may be raised either as:

- Equity with a return generated as dividends derived from market performance or from receipts upon sale of the asset in question, or
- Debt with a fixed return based on interest rates at the time the debt is issued. Equity is generally more costly than debt, but will be available to share more of the risk in a given venture than will debt. The obvious comparison here is in the U.S. capital markets where New York Stock Exchange equity issues (i.e., stocks) compete for funds with fixed rate U.S. Treasury debt issues and corporate commercial paper. Also of note are the many European and Far Eastern stock exchanges and floating rate LIB OR-indexed debt issues.

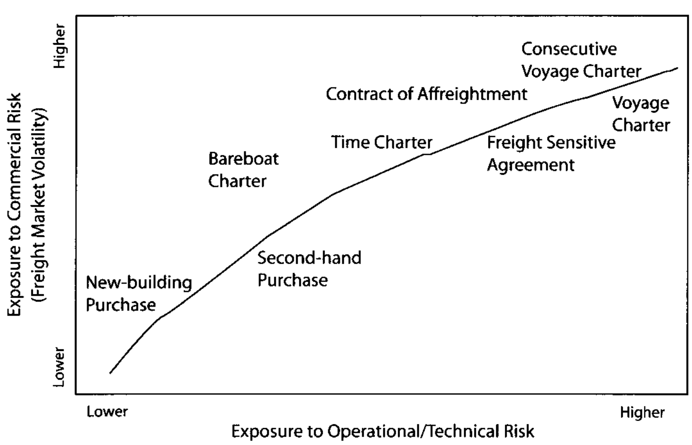

Figure 7.2 Relative Levels of Exposure to Commercial Risk

7.4.4.3 Weighted average cost of capital vs. debt rate

This concept is both an issue of the *cost of finance* as well as the right *discount rate* to use for project economics, both of which are addressed in Subsection 7.4.4.7.

7.4.4.4 Credit ratings and the cost of finance

Agencies such as Standard & Poor's (S&P) or Moody's in the U.S. will assess the credit risk, that is, the risk of default to investors, of a given equity or debt issue or of a given project or venture. The higher the assessed risk, the higher the cost of finance, be it equity or debt. Barring such a formal credit rating, the financial markets will do their own assessment in the way that they price the relative financing of various ventures or ongoing business concerns.

7.4.4.5 Leveraging off project credit or joint venture partner credit

As a subset of the preceding discussion of credit risk, one technique for reducing the cost of finance is for individual participants to combine their strengths in a joint venture (or *project)* and to thereby possibly improve the overall credit rating for the benefit of the joint venture partners (JVPs). This technique requires a high level of cooperation amongst the JVPs as well as covenants to protect the JVPs and creditors in the event of default by one or more of the JVPs. In particular, the JVPs quite probably will have to address the issue of taking *onjoint and several liability* to cover defaults by one or more of their partners.

7.4.4.6 Private vs. public finance

Whether one raises money in the public or private capital markets, or takes it out of retained earnings in the form of working capital, is really a question of the cost of capital; its availability in the various markets; and the capital mix of the company vis a vis return to shareholders. As such, the approach to the capital markets for a given shipping venture will be unique to the venture at hand.

7.4.4.7 Discount rates

The rate at which a DCF model determines the NPV of a set of cash flows is generally dependent on the relative risk (or level of uncertainty) of those cash flows. Generally, the higher the risk (or uncertainty), the higher the discount rate. In this sense, then, contractual or relatively certain cash flows such as term charter revenue or loan payments should be discounted at lower rates than, say, port and fuel costs, fixed operating expenses, or spot charter revenue.

7.4.4.8 Lease vs. purchase

The equivalent interest rate of a lease (EIRL) is a measure whereby an owner may assess the benefit of leasing an asset from a third party v. funding its acquisition with internal resources. In a classic lease/purchase analysis, that discount rate which equates the NPVs ofleasing cash flows and outright purchase cash flows is called the EIRL. If it is less than an owner's debt rate, then leasing is attractive. If more than an owner's debt rate, leasing is unattractive.

7.4.4.9 Inflation rates

Whether high or low, inflation always should be taken into account in any economic analysis of tonnage acquisition alternatives. In the most general sense, cash flows should all include the effects of their own escalators/de-escalators as anticipated over the life of the asset. To the extent individual escalators/de-escalators are unknown or difficult to forecast, then a more general measure of inflation, such as a national price inflator/deflator or gross domestic product inflator/deflator, should be used. In any event, the correct discount rate (constant or then-current dollar) should be used when running DCF economics.

7.4.4.10 Foreign exchange rates

For cash flow analyses involving foreign currencies, a forecast of exchange rates should always be used which is internally consistent with relative inflation and interest rates among the countries at hand. To proceed otherwise is to introduce distortions into the analysis, which might otherwise incorrectly direct an owner to one acquisition mode vs. another.

7.4.4.11 Tax effects

Since tax payments, and credits, represent real economic payments to (or benefits from) central state tax authorities, they should always be included in any rigorous economic analysis of tonnage acquisition alternatives. Of course, as for inflation, the correct discount rate (before- or after-tax) should be used when running DCF economics. It should be noted also that, to the extent that tax laws or tax rates may change over time, sometimes suddenly and drastically, tax effects may introduce a large area of uncertainty, and thereby risk, into long-lived projects like tonnage acquisitions.

7.5 SHIPBUilDING CONTRACT PRICE AND TOTAL PROJECT COST

7.5.1 General

Section 7.4 outlines the myriad of methods that can be used to acquire tonnage. If a vessel is to be constructed for an owner, then the shipyard and vessel owner will first agree on the terms of a shipbuilding contract (14). Amongst other obligations, this document compels the shipyard to build a vessel that meets the technical specifications and contract terms (such as delivery date) and obligates the owner to pay for the vessel at the agreed upon price.

Chapter 9 covers contracts and specifications in detail and shows a typical table of contents for a shipbuilding contract. The shipbuilding contract will typically refer to agreed upon ship construction specifications for all technical requirements of the vessel. The shipbuilding contract will incorporate the commercial requirements of the deal. The owner will have specific contractual requirements that will be important or critical to a successful project and a successful operation. These important commercial requirements will vary from project to project although total project (acquisition) cost is almost always critical.

An acceptable project cost should consider life cycle cost considerations such as fuel consumption and maintenance cost control measures as discussed in Sections 7.2 and 7.3. This section provides background information on typical cost elements that make up the total project cost for constructing a new vessel.

The reader is referred to Chapter 10, which covers pricing and cost estimating.

Acquisition cost is critically important to the commercial shipowner. Shipowners who acquire vessels for a lower total cost than their competitors enjoy a commercial advantage for the life of the vessel. Refer to Chapter 4 for a discussion on acquisition methods the owner may use to help ensure a final competitive shipyard price. Total acquisition cost includes many items in addition to the shipyard contract cost. This total acquisition cost will typically form the basis for a project budget, which will be controlled during project execution. Table 7.x shows a sample summary of the owner's costs for acquiring a large commercial trading vessel. In this example, the owner's total cost to place a new ship in service exceeds the shipyard base price by 8 percent.

7.5.2 Cost Elements

The individual cost elements are discussed as below.

7.5.2.1 Base price of vessel

This is typically the largest of all the cost elements and therefore the one that attracts the most attention. This is the price the owner will pay for the vessel not including any other adjustments that may be necessary under the terms of the contract. Because of its importance, much effort and time is spent negotiating this cost.

It is customary that the owner pays the shipyard the full base price in payments spread out over the duration of the contract. Payments are triggered by certain key events. For instance, the payment terms of a contract may specify 25% due on contract signing, 25% when the keel is laid, 25% on launching, and 25% upon delivery. Opposite extremes of payment terms would be 70% due upon contract signing or alternatively 70% due upon vessel delivery. Earlier payment schedules will usually reduce contract price but an after-tax net present value analysis is necessary to determine the best payment terms from the owner's perspective.

If a foreign shipyard is used, payments in foreign currency may be required and the owner must then recognize that the final cost in his local currency is dependent on foreign exchange rates at the time contract payments become due. This cost impact due to future currency valuation is known as exchange rate risk. Exchange rate risk may be mitigated via the foreign exchange forward market, the currency futures market, or other financial strategies. However, these actions do incur costs. For further details the reader is referred to a standard text on financial markets (15).

TABLE 7.X Sample Owner's Costs for Acquiring a Large Commercial Trading Vessel

Shipyard contract price	
Base price	U.S. $60 000 000
Contract alterations	300 000
Performance incentive adjustments	500 000
Liquidated damages	<0>
Owner-furnished equipment	450 000
Delivery and registration	
Registration fees	50 000
Shipboard personnel training and transportation	100 000
Naming ceremony expenses	50 000
Posit~oningcosts	900 000
Project management	
Pre-contract engineering and administrative	350 000
Post-contract engineering and administrative	580 000
Field supervision	I 200 000
Guarantee	
Guarantee Engineer	30 000
Guarantee administration	20 000
Other	
Duties	a
Others	a
TOTAL PROJECT COST	$64 530 000

7.5.2.2 Contract alterations

During engineering, plan approval, and construction work it is common for the owner or shipyard to request changes from what is specified in the contract specifications. For instance, the owner may request that the shipyard provide a recently developed underwater hull coating system that was not available when the contract was signed. Such a change is a contract alteration and if agreed, may result in increased or decreased cost. Payment for alterations is typically due when the vessel is delivered.

7.5.2.3 Performance incentive adjustments

The contract may include performance incentives that result in increased or decreased payments. For instance, if the vessel is delivered earlier than the contract delivery date, a performance incentive clause in the contract may call for the owner to pay an additional fee to the shipyard.

7.5.2.4 Liquidated damages

Under the terms of the construction contract, liquidated damages may result in reduced payment to the shipyard due to under-performance compared to what is specified under the terms of the construction contract and specifications. For instance, liquidated damages may apply for late delivery, insufficient speed, excessive fuel consumption, or insufficient cargo carrying capacity.

7.5.2.5 Owner-furnished equipment

The owner will usually provide some equipment or outfitting items depending on the terms of the contract. Examples of owner- furnished equipment are shown in Table 7.xI. Depending on the vessel's mission, the owner may also choose to furnish major pieces of specialized equipment.

7.5.2.6 Registration fees

The owner will need to pay registration fees to the flag state country.

7.5.2.7 Shipboard personnel training and transportation

The operating crew will require transportation to the delivery location, which is usually the shipyard. In addition, they may require training for operating new or unfamiliar equipment and systems on the vessel.

7.5.2.8 Naming ceremony expenses

If a naming ceremony is to be held, there will be associated owner's costs.

7.5.2.9 Positioning costs

The constructing shipyard may not be located near the region of operation for the vessel. The time and expenses as-

<u>**TABLE LXI**</u> <u>Examples of Owner-Furnished Equipment</u>

Carpeting
Charts
Chemical supplies
Christening gifts
Cleaning gear & housekeeping supplies
Clothing allowance
Communication equipment
Company forms
Computer hardware
Computer software
Copy machine
Electrical supplies
Entertainment equipment
Exercise equipment
Firefighting, lifesaving, & safety equipment
Galley equipment
General maintenance stores
Immigration & customs forms
Laundry equipment
Lubricants
Lubricant & fuel test equipment
Machinery diagnostic systems and equipment
Machinery spare parts
Medical stores & equipment
Metals
Mooring wires and ropes
Nautical publications
Navigation & deck supplies
Navigation systems
Office equipment & supplies
Packing & gaskets
Paint & painting supplies
Pilot hoist
Pipe, valves & fittings
Portable tank ventilators
Provisions
Registry forms
Rope & line
Steward equipment
Tools, hand & power
Training equipment & materials
Welding supplies

sociated with positioning the vessel after delivery can be a significant cost element to the owner.

7.5.2.10 Pre-contract engineering and administrative

This cost element covers the owner's efforts leading up to the signing of the construction contract. Engineering work, specification negotiations, and contract negotiations usually constitute the majority of these costs.

7.5.2.11 Post-contract engineering and administrative

Home office project management costs are captured in this cost element such as engineering studies, plan approval, management reporting, and record keeping.

7.5.2.12 Field supervision

It is common for the owner to have a team of representatives in the shipyard during construction. These representatives monitor progress, inspect workmanship and may also provide project management functions.

7.5.2.13 Guarantee Engineer

For ocean going vessels, the shipyard may be requested to provide an on-board Guarantee Engineer to ride on the vessel for some limited period of time (such as three months or more). The purpose of this shipyard supplied Engineer is to facilitate rectification of post-delivery technical problems and the settlement of guarantee claims.

7.5.2.14 Guarantee administration

Administration of guarantee claims during the guarantee period and final settlement can incur additional labor costs for the owner.

7.5.2.15 Others

Each vessel acquisition project will usually have costs that fall in this category such as duties due, legal expenses, financing costs, and bank guarantee fees.

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7.7 USEFUL READINGS

7.7.1 Periodicals

Fairplay International Shipping Weekly (Coulsdon, Surrey, U.K.)
Lloyd's Shipping Economist (London)
Lloyd's Ship Manager (London)
Lloyd's Shipping Index (London)
Marine Money International (Stamford, Connecticut)

7.7.2 Other Information Sources

Drewry's Shipping Consultants (London)
Japan Maritime Research Institute (Tokyo)
U.S. Maritime Administration (Washington)

Chapter 8.

Classification and Regulatory Requirements

Glenn Ashe and Jeffrey Lantz

8.1 INTRODUCTION

Verification that a system complies with mutually agreed-upon criteria is at the heart of any successful contractually established acquisition. Ordinarily, these criteria are documented in a contract, which conveys to the supplier the expectations of the purchaser. In addition, these criteria can then form the basis of a through-life maintenance plan and can provide an indication of proper stewardship of the asset. Clearly conveying these expectations to those who must meet them is a challenge and, as acquired items increase in complexity, the probability of misunderstanding or variance in interpretation of requirements increases. Oftentimes, a mechanism, which employs third-party certification agents without inherent interests to verify compliance, is implemented to verify compliance to established standards.

In the marine industry, there are three primary groups into which the criteria, which define the acceptability of a vessel or other complex system, can be placed. These are classification society rules, regulatory requirements and shipowner requirements. Recognizing the responsibility of stewardship that should be assumed by the ship owners and operators of such a complex and pervasive system, the industry itself has established a process called classification by which standards related to the safety and fitness of the system to meet its intended purpose are maintained and applied. This process is truly unique and includes participation from all aspects of the industry ensuring that the standards and the processes for applying them are comprehensive without being punitive.

Participation in this classification process cannot be mandated upon all shipowners and operators of marine systems and, therefore, a complementary process which is government driven has been established. This is because marine commerce represents such a significant portion of world economy, touches almost all nations and is dynamic in nature. Thus, it has been found necessary to include baseline acceptability requirements in the set of criteria that represent the expectations of society (the general public) insofar as the protection of human life and the environment is concerned. These criteria are regulatory in nature and are established and implemented through conventions, treaties, laws and regulations. Most governments recognize classification as sufficient for satisfying a large portion of these requirements and a close relationship between classification societies and governmental marine safety organizations has developed over the years.

Finally, there is a large body of requirements, which do not necessarily fall into either of these categories but is of paramount interest to the shipowner (see Chapter 7–Mission and Owner's Requirements). These include characteristics, which affect the mission performance or economic viability of the asset such as speed, cargo throughput, crew habitability as well as many others. These can be grouped as shipowner requirements and are usually conveyed as specific requirements in the contract. Usually shipowners rely upon classification society rules and governmental statutory requirements to form the core of the criteria, which will define their vessel and add to those the shipowner requirements, which will shape the vessel to its specific mission.

8.2 CLASSIFICATION

8.2.1 Background

Classification Societies trace their roots back to a decision made by a number of leading underwriters in a London coffee house name Lloyd's in the year 1760. At that time, due to the emerging need to better assess vessel risk for the purpose of determining adequate insurance premiums, the leading underwriters established an organization, which would look at the sailing ships requesting coverage and provide a subjective assessment of the strength of the vessel for the intended voyage as well as the capability of the Master. The organization was named Lloyd's Register of Shipping. In the course of conducting these assessments the company recorded pertinent findings, subsequently grading the vessel according to a numerical system which provided an indication of the relative risk involved in underwriting the ship.

These records were published in a volume referred to as the *Register* and the contents therein were made available to all participating underwriters. Recognizing the value of this developing process of industry self-regulation, the British government provided a number of governing principals intended to ensure the fidelity and integrity of the process, which remain in force in most classification societies today. One of the most important recommendations was that the governing body of the classification society should include members from all sectors of the shipping community; shipowners, shipbuilders, and underwriters. This helped guarantee the impartiality of the process and ensured that decisions would take into account all relevant viewpoints.

There were three other key points:

1. classification should be assigned in accordance with established rules,
2. the classification society should have a permanent, qualified staff, and
3. the society should not be governmental.

This last is important in that it meant that politics would not govern decisions, which should be made on technical merit. This process became commonly known as classification, and hence the organizations, which came into existence to satisfy such needs, became known as classification societies.

Although it is rooted in a service to underwriters, the process has become much more. The mission of a classification society is to promote the security oflife, property and the natural environment through the development and verification of standards for the design, construction and maintenance of marine related facilities. The basis for a class society's success in carrying out this mission rests in the recognition by the marketplace of the value that it adds to the assets in question. Thus, shipowners and their underwriters look to classification as an attestation that their vessels are built and maintained to a level which protects their investment; govermnent administrations look to class societies as partners in carrying out their duties as flag and port state marine regulators; and the remainder of the marine industry relies on classification standards as the baseline for assessing vessel fitness for intended purpose. Over the intervening years a number of such classification societies emerged to satisfy the increasingly international nature of the emerging marine insurance market. The leading societies, being involved in very similar work, established an association (The International Association of Classification Societies) to better standardize their application of technology and methods of operation.

8.2.2 International Association of Classification Societies (lACS)

The International Association of Classification Societies (lACS) can trace its origin back to the International Conference on Load Lines of 1930, which recommended that classification societies recognized by governments under Article 9 of the Load Line Convention of 1930 *should confer from time to time ... with a view to securing as much uniformity as possible in the application of the standards of strength on which freeboard is based ...*

In 1939, the first conference of international classification societies was hosted by Registro Italiano Navale in Rome and was attended by representatives of the American Bureau of Shipping, Bureau Veritas, Det Norske Veritas, Germanischer Lloyd, Lloyd's Register of Shipping, and Nippon Kaiji Kyokai. During this conference it was agreed that cooperation between classification societies should be further developed and conferences should be convened as deemed desirable. There was no formal organization at that time.

The next conference was held in Paris in 1955 with Bureau Veritas as host, followed by meetings in London, 1959 (Lloyd's Register); New York, 1965 (American Bureau of Shipping); and Oslo, 1968 (Det Norske Veritas). It was during this Oslo conference that the establishment of an InternationalAssociation of Classification Societies was agreed upon.

The International Association of Classification Societies was formally established in 1968 with three main purposes:

1. to promote improvement of standards of safety at sea,
2. to consult and cooperate with relevant international and marine organizations, and
3. to maintain close cooperation with the world's maritime industries.

Membership in lACS is held by ten leading classification societies:

American Bureau of Shipping	(ABS)
Bureau Veritas	(BV)
China Classification Society	(CCS)
Det Norske Veritas	(DNV)
Germanischer Lloyd	(GL)
Korean Register of Shipping	(KR)
Lloyd's Register of Shipping	(LR)
Maritime Register of Shipping	(RS)
Nippon Kaiji Kyokai	(NK)
Registro Italiano Navale	(RINa)

In addition, the Croatian Register of Shipping (CRS) and the Indian Register of Shipping (IRS) are recognized as associate members.

The government body ofIACS is the council, which consists of one senior executive from each member society. The council meets regularly once a year to conduct the activities of the association. Meetings to deal with matters of immediate concern may be held more frequently and at short notice. The principal objective of the council is to establish the general policy of the association, to solve any policy problems, and to plan for future activities.

The council also considers and adopts resolutions on technical issues within the classification societies' scope of work. Numerous *unified requirements* (URs), and *unified interpretations* (Uls) of international codes and conventions have been adopted by the council. Typical examples ofIACS unified requirements are:

- minimum longitudinal strength standard,
- special hull surveys of oil tankers,
- loading guidance information,
- use of steel grades for various hull members,
- hull and machinery steel castings,
- cargo containment on gas tankers,
- prototype testing and test measurement on tank containers,
- inert-gas generating installations on vessels carrying oil in bulk,
- fire protection of machinery spaces, and
- survey of hatch covers and coamings.

Between the regular meetings of the council, the general policy group, a subsidiary body of the association, meets to deal with current affairs and progress of the lACS workmg groups.

Working groups are established by the council in accordance with the character of the association. They include both permanent working parties and ad hoc groups. Long before the formal foundation of lACS was established, a number of working parties existed to carry out studies of specific topics. The first of these was the working party on hull structural steel, established in 1957. It produced *Unified Requirement No. 1* for hull structural steels.

Following are the general responsibilities of the workmg groups:

- to draft unified rules and requirements between the member societies,
- to draft responses to requests of the International Maritime Organization (IMO) and to prepare unified, interpretations of conventions, resolutions, guides, and codes,
- to identify problems related to the working group's area of activity and to propose lACS action, and
- to monitor the work organizations related to the expertise of the working groups and to report to the council.

The following topics are the responsibility of individual working groups:

- containers,
- drilling units,
- electrical systems,
- engmes,
- fire protection,
- gas and chemical tankers,
- hull damages,
- inland waterway vessels,
- marine pollution,
- materials and welding,
- mooring and anchoring,
- pipes and pressure vessels,
- strength of ships,
- subdivision, stability, and load lines, and
- survey, reporting, and certification.

Since 1969, lACS has been granted consultative status with IMO. A representative of IMO has since then attended lACS Council meetings, and lACS representatives have regularly participated as observers at the meeting of the Assembly, the Maritime Safety Committee, the Marine Environment Protection Committee, and different subcommittees and working groups of IMO. Recognizing the importance of a mutual relationship between lACS and the increasing contribution of lACS work to IMO activity, in 1976 the lACS Council appointed a permanent representative to IMO.

lACS is the only nongovernmental organization with observer status at IMO able to develop rules. These rules, implemented by its member societies, are accepted by the maritime community as technical standards. In areas where IMO intends to establish detailed technical or procedural requirements, lACS endeavors to ensure that these requirements are easily applicable and as clear and unambiguous as possible.

lACS liaises with international organizations for exchange of views and information on matters of mutual interest. This ensures that the views of the industry are taken into consideration in the work of lACS. Examples of such international organizations are International Marine Insurers, International Chamber of Shipping, Oil Companies International Marine Forum, Society of International Gas Tanker and Terminal Operators Ltd., International Standardization Organization, and Economic Commission for Europe.

8.2.3 Organization and Management of the American Bureau of Shipping

The American Bureau of Shipping has no capital stock and pays no dividends. It is a nonprofit, non-governmental ship classification society. The income of ABS is derived from fees for the classification and survey (periodic in-service inspection) of marine structures. All funds are used solely for the performance of services, and any surplus of receipts in anyone year is used for the extension and improvement of such services.

Management responsibilities are vested in the Board of Directors and Council chosen from the some eight hundred members of ABS. The members-whose purpose is to promote and support the mission of ABS---compri~e shipowners, shipbuilders, naval architects, marine engineers, engine builders, material manufacturers, marine underwriters, government representatives and other persons eminent in their marine and related fields of endeavor. None of the members receive any compensation for services rendered. Organized and managed in this manner, and with this wide spectrum of interests involved as members, the American Bureau of Shipping provides the industry with a recognized organization for self-regulation.

As an international technical organization it is essential that ABS be current with marine-related developments worldwide. ABS accomplishes this through a general committee structure consisting of individuals eminent in marine and related industries. The general committees also serve as a forum for ABS members and management worldwide.

8.2.4 The Classification Process

Classification societies apply this process today for the world's shipping community with their surveyors carrying out continuous surveys on a vessel from keel laying to scrapping to ensure adherence to the Rules. This encompasses such duties as witnessing tests of materials for hull and machinery items at the place of manufacture or fabrication; surveying the building of the hull and its machinery, boilers, and vital auxiliaries; attending sea trials and surveying the vessel throughout its life. In Africa, Asia, Europe, Australia, and the Americas-wherever ships are being built, repaired, or operated-the surveyor is on call twenty-four hours a day.

Engineers conduct systematic evaluation of the hull and machinery plans for a vessel to determine the structural and mechanical adequacy of the design according to the Rules. Engineers are strategically located in offices around the world enabling them to maintain person-to-person contact with shipowners, designers, and builders in the development and evaluation of plans. Through the years, the technical staff has increased its sophistication and technological resources in handling new designs and in sharing its expertise with the maritime industry. It is this expertise embodied in its staffs of surveyors and engineers spread over six continents that enables the classification society to maintain its unique position in the marine industry.

The primary means by which a classification society pursues its mission is through classification of ships and other marine structures. Classification is a procedure involving:

- technical plan review,
- surveys during construction,
- acceptance by the Classification Committee,
- subsequent periodic surveys for maintenance of class, and
- the development of standards, known as Rules.

8.2.4.1 Technical plan review

When a shipowner first requests that the vessel or structure be classed, the shipyard or design agent presents design drawings and calculations to the class society for a systematic detailed review for compliance with the Rules. Engineers review the plans to verify that the structural and mechanical details conform to the Rule requirements. In this way, the classification society is able to determine whether the design is adequate in its structural and mechanical concept and, therefore, suitable for production. Essential to maximizing the "value added" potential of this part of the process, the engineering staff is available for continuous consultation with the shipowner and designer.

8.2.4.2 Surveys during construction

After a design has been reviewed and found to be in conformance with the Rules, field surveyors *live with the vessel* at the shipyard from keel laying to delivery to verify that: the approved plans are followed, good workmanship practices are applied, and the Rules are adhered to in all respects. During the construction of a vessel built to class, surveyors witness, at the place of manufacture or fabrication, the tests of materials for hull and certain items of machinery, as required by the Rules. They also survey the building, installation and testing of the structural and principal mechanical and electrical systems. Throughout the time of construction class surveyors and engineers maintain an ongoing dialogue with the shipowner and builder to make sure the Rules are understood and adhered to, and also to assist in resolving differences that may arise.

8.2.4.3 Sea trials/class committee

When completed, a vessel undergoes sea trials attended by field surveyors to verify that the vessel performs according to Rule requirements. The vessel's credentials are then presented to the Classification Committee (members who are appointed from the maritime industry, statutory body representatives, and class society officers), which, based on collective experience and recommendations from the class society staff, assesses the vessel's compliance with the Rules. Provided all is in order, the vessel is accepted into class and formal certification is issued. The vessel's classification information, characteristics and other particulars then are entered into the class society Record or Register-the registry of vessels classed.

8.2.4.4 Surveys after construction

Though a new vessel may be granted classification and thereby judged fit for its intended service, such status is not automatically retained throughout its service life. As the rigors of sea can be wearing on a vessel's hull and machinery, the society conducts periodic surveys to determine whether a vessel is being maintained in a condition worthy of retaining classification status. As specified in the Rules, shipowners must present their vessels on a periodic basis for survey of hull and machinery items. Also, should there be any reason to believe that a classed vessel has sustained damage that may affect classification status, it is incumbent upon the shipowner to so inform the society. Upon request, surveyors would then survey the vessel to determine whether it meets the Rules and, if not, recommend appropriate repairs to maintain classification.

8.2.4.5 Classification standards

As is clear from the previous information another essential aspect of the classification function is the development of the standards, known as Rules, to be used. The Rules are established from principles of naval architecture, marine engineering, and other engineering disciplines that have proven satisfactory by service experience and systematic analysis.

Classification societies ordinarily promulgate and periodically update their Rules through technical committees composed of individuals internationally eminent in their marine field and who serve without compensation. These committees permit the society to maintain close contact with interests in various geographic regions and with various technological and scientific disciplines. The committee arrangement has the distinct advantage of allowing all segments, including the governments, of the industry to participate in developing the various Rules. As a result of these procedures the Rules are both authoritative and impartial.

8.2.5 What Classification Represents

The responsibility of the classification society is to assure that the ships and marine structures presented to it comply with Rules that the society has established for design, construction, and periodic survey. Classification itself does not judge the economic viability of a vessel, neither is the society in a position to judge whether a vessel is ultimately employed according to the stated intended service for which it was classed. Nor can the classification society assume responsibility for managerial decisions of a shipowner or operator concerning crewing practices or operation of a classed vessel. It records, reports, and recommends in accordance with what is seen at the time of a vessel's construction and subsequent surveys.

Through its classification survey procedure it is the intent of the society to prevent a vessel from falling into a substandard condition. If a vessel should be found to be in such a state and the recommendations of the classification society are not followed, then the society has no choice but to suspend or cancel classification.

8.2.6 Naval Classification

Increasingly, navies are recognizing the need to leverage successful commercial mechanisms in order to accomplish necessary roles in a more cost effective manner and have begun to investigate the application of classification society processes in their vessel certification efforts. This currently is being implemented to varying degrees in several navies around the world and it is yet to be determined how the final models will evolve. Several classification societies have Naval Ship Classification Rules in place. The general vision is a continuing partnership between the navy and the classification society for the purpose of establishing, husbanding and implementing the collection of standards against which the acceptability of naval vessels will be measured. The exact nature of this partnership will have to evolve but will be set up so as to take advantage of the skill sets and expertise available. Thus, the classification society would focus on the areas where it has traditionally been a technology leader-hull, mechanical and electrical (H, M &E) systems-enabling the navy to concentrate its resources in the areas unique to naval vessels including interface with those primary to the class society. Integral to this will be the input, review and counsel of shipbuilding industry technical experts. In essence, a *virtual classification society* for the navy would evolve with:

- standards development and maintenance provided through a technical committee structure with navy leadership and industry participation,
- design review and approval (where proposed by industry or required by the navy) carried out by a team of engineers drawing from the class society and the navy and other subject matter experts as might be necessary to ensure acceptability,
- selected system level certifications being conducted by the class society as the Navy's trusted agent, and
- construction oversight and approval accomplished by a team like that previously described.

Through-life survey would be modeled in a similar manner.

It is understood by all involved that the navy, just like its commercial shipowner counterpart, will retain technical authority and ultimate responsibility for the fitness of its assets. The classification process and the resources that come with that will function, just as they do in the commercial world, as a tool for the shipowner (in this case, the navy) to carry out the responsibility as a steward of high value assets and the environment. The classification process will provide an established, time-tested and documented mechanism for certification-a yardstick against which vessel acceptability can be judged and a consistent baseline for industry to build upon.

8.3 INTERNATIONAL STATUTORY REQUIREMENTS

As mentioned earlier, in addition to classification societies' standards or rules, there are also governmental or statutory requirements to protect the interests of society and the general public with regard to safety and environmental concerns as they relate to the marine industry. These standards exist primarily at the international and national levels. However, there are instances of regional and local standards. It is necessary for any maritime business to be aware of the various standards and ensure that compliance with all those that are applicable has been achieved.

Internationally accepted standards are generally only applicable to oceangoing vessels operating between different countries. As such they provide a minimum level of safety and environmental protection for vessels when operating on the high seas. Additionally, and perhaps more importantly, they also provide assurances to the world's countries .that this same minimum level of safety and environmental 'protection will be provided in their national waters when these oceangoing vessels, regardless of flag, operate in their ports. Today, international standards are developed, agreed upon and implemented through the International Maritime Organization (IMO).

8.3.1 International Maritime Organization

The convention that founded the International Maritime Organization was adopted on March 6, 1948, by the United Nations Maritime Conference. The convention was then known as the Convention on the Inter-Governmental Maritime Consultative Organization, and it entered into force on March 17, 1958, thus establishing the IMCO. This new organization was inaugurated on January 6, 1959, when the assembly held its first session. The name of the organization was changed to the International Maritime Organization on May 22, 1982, in accordance with an amendment to the convention that entered into force on that date.

When the United Nations Maritime Conference first met, it recognized that the most effective means to improve the safety standards of the international shipping community would be through an international forum devoted exclusively to maritime matters. Hence, the purposes of the organization, as stated in Article lea) of the convention, are *to provide machinery for cooperation among Governments in the field of governmental regulation and practices relating to technical matters of all kinds affecting shipping engaged in international trade; to encourage andfacilitate the general adoption of the highest practicable standards in matters concerning maritime safety, efficiency of navigation and prevention and control of marine pollution from ships.*

Because the IMO is an international forum and not an executive body, it has no powers of enforcement or initiative. Instead, its member states have the power to initiate proposals, to conduct or commission research, and to implement decisions made with regard to maritime standards. The IMO Secretariat is limited to encouraging member states to address issues raised with the IMO.

8.3.1.1 Organization

The organization consists of an Assembly, a Council, and four main committees: The Maritime Safety Committee (MSC), Marine Environment Protection Committee (MEPC), Legal Committee, and Technical Cooperation Committee. There are also a number of subcommittees of the main technical committees, as well a Facilitation Committee.

Given this structure, the Assembly is the highest governing body of the IMO. It consists of all member states meeting every two years in regular sessions. Extra sessions may be held outside of the regular sessions, if necessary. The Assembly approves the work program, votes the budget, and determines the financial arrangements of the IMO. The Assembly also elects the Council.

The Council is the executive organ of IMO and is responsible, under the Assembly, for supervising the work of the Organization. The Council, between sessions of the Assembly, carries out all the duties of the Assembly except for making recommendations to governments on maritime safety and pollution prevention, which are the sole responsibility of the Assembly. The following are the Council's other functions:

- coordinate the activities of the organs of the organization,
- consider the draft work program and budget estimates of the organization and submit them to the Assembly,
- receive reports and proposals of the committees and other organs and submit them to the Assembly and member states, with comments and recommendations,
- appoint the secretary-general, subject to the approval of the Assembly, and
- enter into agreements or arrangements concerning the relationship of the Organization with other organizations, subject to approval by the Assembly.

The Council consists of forty member states elected for two-year terms by the Assembly. The IMO Convention requires that when electing the members of the Council, the Assembly shall comply with the following three criteria: 1. ten shall be states with the largest interest in providing international shipping services., 2. eight shall be other states with the largest interest in international shipping, and 3. twenty shall be states not selected under (1) or (2) above that have special interests in maritime transport or navigation, and whose election will ensure representation of all major geographic areas of the world.

The *Maritime Safety Committee* (MSC) is the most senior technical body of the Organization. All member states are part of the MSC, and the functions of the MSC are to *consider any matter within the scope of navigation, construction and equipment of vessels, manning from a safety standpoint, rules for the prevention of collisions, handling of dangerous cargoes, maritime safety procedures and requirements, hydrographic information, logbooks and navigational records, marine casualty investigation, salvage and rescue, and any other matters directly affecting maritime safety.*

MSC also has the responsibility to provide a mechanism to perform any functions assigned to it by the IMO Convention or any duty within its scope of work that may be assigned to it by or under any international instrument and accepted by the organization. It also is required to consider and submit recommendations and guidelines on safety for possible adoption by the assembly.

MSC also operates with several subcommittees appropriately titled with the subjects with which they deal: Safety of Navigation (NAV); Radio communications and Search and Rescue (COMSAR); Standards of Training and Watch keeping (STW); Dangerous Goods, Solid Cargoes and Containers (DSC); Ship Design and Equipment, including lifesaving equipment (DE); Fire Protection (FP); Stability and Load Lines and Fishing Vessel Safety (SLF); and Bulk Liquids and Gases (BLG). In April of 1993, a new subcommittee was formed to deal with the numerous problems flag states, particularly those associated with third world nations, experience when implementing the regulations of the various conventions. This new subcommittee is called the Flag State Implementation Subcommittee (FSI).

Like MSC, the *Marine Environment Protection Committee* (MEPC) is also composed of all member states. However, MEPC is required to consider any matter within the scope of the organization concerned with prevention and control of pollution from ships. These duties include the adoption and amendment of conventions and other regulations and measures to ensure their enforcement. The subcommittees reporting to MSC also report MEPC when addressing pollution matters.

Because of the legal issues involved in the organization's activities and work, the *Committee on Technical Cooperation* directs and coordinates this activity with the *Legal Committee.* These two committees are composed of all member states. Simplification and minimization of documentation in international maritime traffic is the responsibility of the *Facilitation Committee,* a subsidiary of the council. Participation in this committee is open to all member states of IMO.

As stated earlier, the IMO Secretariat is limited to encouraging member states to address issues raised with the IMO. The secretariat of IMO consists of the secretary-general and nearly three hundred personnel based at the headquarters in London, United Kingdom.

8.3.1.2 IMO codes and conventions

To achieve its purposes of *developing the highest practicable standards in matters concerning maritime safety, efficiency of navigation, and prevention and control of marine pollution from ships,* IMO has developed and adopted nearly forty conventions and protocols as well as hundreds of codes and recommendations. A committee or a subcommittee normally does the initial work performed on a convention. The committee's work, a draft instrument, is then submitted to a conference to which delegations from all states within the United Nations system (including states that may not be IMO member states) are invited. The conference adopts a *final text* by *general consensus* rather than by vote. The final text then is submitted to governments for ratification.

A convention enters into force after fulfilling certain requirements that usually include adoption of the text at a United Nations conference followed by ratification by a specified number of countries. Generally, the more important the convention, the more stringent are the requirements for entering into force. For example, some conventions stipulate that 50% ofthe world's shipping by a minimum number of countries must ratify the conventions before they enter into force. Amendments to conventions are usually ratified differently. They enter into force through a *tacit acceptance* process. Member states are assumed to accept the amendment unless a specific reservation to the contrary is filed with the IMO Secretary. If rejections have been received within a specific time period from member states representing a minimum amount of world tonnage, the amendment will not enter into force.

Observance ofthe convention's requirements is mandatory for the countries that are party to it. On the other hand, codes (e.g., gas or chemical codes) are resolutions (i.e., recommendations) adopted by the assembly and are not as binding. Resolutions normally *invite* or *urge* participating governments to enact the contents through their own national requirements, preferably in their entirety and not partially.

Ofthe forty conventions and protocols adopted by IMO, the four that have probably had the most profound effect on international shipping with respect to ship design and construction are the International Convention for Safety of Life at Sea (SOLAS), International Convention for the Prevention of Pollution from Ships (MARPOL), International Convention of Load Lines (ICLL), and the International Convention of Tonnage Measurement of Ships (Tonnage).

8.3.2 SOLAS Convention

As discussed earlier, IMO is principally concerned with safety at sea and mitigating the possibilities of marine environmental pollution. Of all the international conventions addressing maritime safety, the most significant is the International Convention for the Safety of Life at Sea (SOLAS). As will be discussed, the SOLAS Convention has undergone and will continue to undergo numerous revisions. Generally, the SOLAS Convention provides requirements that address six main categories of vessel safety: navigation, design, communication, lifesaving appliances, fire protection, and safety management.

Although the first version of the SOLAS Convention was adopted at the 1914 International SOLAS Conference, it never entered into force. Yet, four other versions of SOLAS were developed, adopted and eventually entered into force. The second version was adopted in 1929 and entered into force in 1933. The third version was adopted in 1948 and entered into force in 1952. The fourth version was adopted in 1960 and entered into force in 1965. The latest version was adopted in 1974 (SOLAS 1974) and entered into force in 1980.

Each version enhanced the previous version's safety requirements and was based on the latest technology or marine accident investigations. For instance, the 1912 sinking of the ocean liner *Titanic* led to the development of the 1914 SOLAS Convention, which then was amended in 1929. Moreover, significant improvements to subdivision and stability standards, emergency services, structural fire protection, and collision regulations were included in the 1948 SOLAS Convention.

The 1960 SOLAS Convention was the first SOLAS Convention developed under IMCO. Numerous technical improvements were made for cargo ships requirements, including emergency power and lighting and fire protection. Six sets of amendments to the 1960 SOLAS Convention were adopted during the eight years following the convention's entry into force. These amendments included safety measures specific to tankers, automatic pilot requirements, and ship borne navigational equipment requirements, among others.

8.3.2.1 SOLAS1974

At the present time, the convention that is applied is the 1974 SOLAS Convention. The following discussion provides a brief summary of the 1974 SOLAS Convention:

Chapter I provides the format of the certificates that are issued to signify compliance with SOLAS as well as the minimum survey periods. This chapter also empowers the port state to carry out port state control, which ensures that ships calling at their ports possess valid certificates and are in compliance with the SOLAS requirements. If ships are not in compliance, this chapter allows the port state to take appropriate action to detain the ship and notify IMO.

Chapter II-I addresses minimum extents of watertight integrity and subdivision governed by a probability of collision criteria. Extensive requirements for electrical and machinery installations and control systems also are included. These requirements ensure that services essential to the safety of the vessel and its crew and passengers are maintained under normal and emergency conditions.

Chapter II-2 contains detailed fire safety provisions for various types of vessels based on the following principles:

- maintenance of thermal and structural boundaries,
- separation of accommodation spaces,
- limited use of combustible material,
- fire detection in zone of origin,
- fire containment and extinction in zone of origin,
- protection of means of escape or firefighting access,
- availability of firefighting appliances, and
- minimizing the possibility of cargo vapor ignition.

Chapter III provides requirements for the amount and location of lifesaving appliances specific to each type of vessel, as well as details concerning the capacity and construction of the different lifesaving appliances.

Chapter IV provides for radio equipment specifications and operating obligations of the crew.

Chapter V provides for navigational requirements directed at the coast state as well as requirements for ship borne navigational equipment and pilot ladders.

Chapter VI provides stowage provisions when loading grain. Stability criteria particular to each loading condition are included, taking into account potential shifting of cargo and heeling moments.

Chapter VII delegates to contracting states the mandatory responsibility to adopt procedures to handling dangerous goods. For this purpose, this chapter refers to the International Maritime Dangerous Goods Code (IMDG).

Chapter VIII gives very basic principles concerning atomic radiation safety on nuclear ships (except ships of war) and refers to the International Atomic Energy Association for special control in ports.

Chapter IX requires that specific vessels and their shore-based operating company meet the requirements of he International Safety Management Code (ISM Code), which is contained in an assembly resolution. The resolution, based on the appropriate sections of the ISO 9000 series, calls for periodic inspections and maintenance of conditions to provide for safety and environmental protection.

Chapter X makes the International Code of Safety for High-Speed Craft (HSC Code) mandatory for high-speed craft built on or after I January 1996. A high speed craft is defined as a craft capable of a maximum speed in meters per second equal to or exceeding $3.7V^{0.1667}$ where V is the craft's displacement in cubic meters. It applies to passenger craft that do not proceed on voyages for more than four hours and cargo craft of 500 gross tons and above that do not proceed on voyages for more than eight hours from a harbor of safe refuge. Two principles of the code are used to categorize requirements for the type of passenger craft as either Category A or Category B. A reduction in passive and active passenger protection is permitted for Category A craft on the basis that sufficient rescue resources are available to evacuate the craft at any point within its route within four hours and it is limited to craft with a passenger count of not more than 450. The requirements for Category B recognize the need to provide sufficient refuge for passenger safety and the need to be able to proceed to navigate safely. Chapter X was adopted in May 1994 and entered into force on 1 January 1996. A new HSC Code was adopted in December 2000 and it applies to craft built on or after I July 2002.

Chapter XI-1 includes special measures to enhance maritime safety and clarifies requirements relating to authorization of recognized organizations (responsible for carrying out surveys and inspections on behalf of Administrations); enhanced surveys for bulk carriers and tankers; ship identification number scheme; and port state control on operational requirements.

Chapter XI-2 contains special measures to enhance maritime security. This chapter applies to passenger ships and cargo ships of 500 gross tonnage and upwards, including high speed craft, mobile offshore drilling units and port facilities serving such ships engaged on international voyages. It invokes the International Ship and Port Facilities Security Code (ISPS Code) and includes requirements that ship and port facility security assessments are carried out and that ship and port facility security plans are developed, implemented and reviewed in accordance with the ISPS Code. It requires Administrations to set security levels and requires ships to comply with requirements established by Administrations and Contracting Governments for the security level. It confirms the role of the Master in exercising professional judgment to maintain the security of the ship. It requires all ships to be provided with a ship security alert system, which when activated, initiates and transmits a covert ship-to-shore security alert to a competent authority designated by the Administration. The chapter also covers providing information to IMO, the control of ships in port, and the specific responsibilities of Companies.

Chapter XII contains additional safety measures for bulk carriers. It includes structural requirements for new bulk carriers over 150 meters in length built after 1 July 1999 carrying cargoes with a density of 1,000 kg/m3 and above and also includes specific structural requirements for existing bulk carriers carrying cargoes with a density of 1,780 kg/m3 and above - these include cargoes such as iron ore, pig iron, steel, bauxite and cement. Cargoes with a density above 1,000 kg/m3 but below 1,780 kg/m3 include grains, such as wheat and rice, and timber.

8.3.2.2 Amendments and protocols to SOLAS 1974

The 1974 SaLAS Convention has been amended several times by protocols and amendments. The following paragraphs provide a brief, chronological summary of the significant changes:

1978 Protocol was adopted at the International Conference on Tanker Safety and Pollution Prevention, which was convened in response to a spate of tanker accidents in 1976-1977. It made a number of important changes to Chapter I, including the introduction of unscheduled inspections and/or mandatory annual surveys and the strengthening of Port State Control requirements. Chapters II-I, 11-2 and V also were improved. Inert gas systems were required for new and certain existing tankers. All tankers of 10 000 gross tons and above were required to have two remote steering gear control systems and two or more identical power units and the capability of operating the rudder with one or more power units. In addition, it included the requirements that all ships of 1600 gross tons be equipped with radar and that all ships of 10 000 gross tons and above shall have two radars, each capable of being operated independently.

1981 Amendments rewrote and updated Chapters II-I and 11-2 along with important changes to Chapter V. Following the AMOCO CADIZ disaster and the 1978 Protocol, duplicate and separate steering gear control systems were required for tankers. The fire safety provisions were strengthened for cargo ships that were based on the principles of: separation of accommodation spaces from the remainder of the ship by thermal and structural boundaries; protection of means of escape; early detection, containment or extinction of any fire, and restricted use of combustible materials. Other amendments included provisions related to halon extinguishing systems, special requirements for ships carrying dangerous goods, and inert gas systems. Changes to Chapter V included requirements for specific navigation equipment to be carried on the ship's bridge.

1983 Amendments provided requirements for separation of accommodations from machinery and other high-risk spaces. Significant changes were introduced concerning lifesaving appliances including their design, capacity, and the use and placement of partially and totally enclosed lifeboats. Requirements for immersion suits and improvements in locating ship's survivor (EPIRBs, additional requirements for lifebuoys and lifejackets) were introduced. The amendments also introduced into Chapter VII a reference to two new codes (Gas Carrier Code and Bulk Chemical Carrier Codes).

April 1988 *Amendments* focused on maintaining and monitoring the watertight integrity of passenger - Ro/Ro vessels in light of the *Herald of Free Enterprise* sinking.

October 1988 *Amendments* furthered requirements for damage residual stability, expanded the stability information supplied to the master, and required periodic (five-year intervals) lightweight surveys, based on the *Herald of Free Enterprise* disaster.

1988 Protocol, which entered into force in February 2000, introduced a new harmonized system of surveys and certification (HSSC) to harmonize with two other Conventions, Load Lines and MARPOL 73/78. This alleviates problems caused by the fact that as requirements in the three instruments vary and ships may have been obliged to go into dry-dock for a survey required by one convention shortly after being surveyed in connection with another. By enabling the required surveys to be carried out at the same time, the system is intended to reduce costs for shipowners and administrations alike.

November 1988 *Amendments* completed almost twenty years of work concerning radio communications for the Global Maritime Distress and Safety System (GMDSS) and entered into force in February 1992. These amendments base communication capabilities on the vessel's area of operation (rather than the vessel's tonnage) and phase out Morse code, utilizing more advanced technologies offered by satellite communications.

1989 Amendments reduced the amount of openings in watertight bulkheads and required that power-operated sliding doors be fitted in all new passenger ships. Safety improvements in fire extinguishing, smoke detection, and separation of spaces containing fuel were included.

1990 Amendments changed the philosophy of evaluating damage stability and subdivision for dry cargo ships from the "deterministic" to the "probabilistic" method. These amendments provide a more realistic damage scenario based on statistical evidence.

1991 Amendments extended Chapter VI *(Carriage of Grain in Bulk)* to include storing and securing other cargoes, such as timber. Fire safety provisions to accommodate new passenger ship designs were also included.

April 1992 *Amendments* were somewhat of a landmark for IMO since they required significant improvements to be made to existing passenger and passenger-RO/RO ships. Notable among the new requirements is the need for sprinkler systems and smoke detection systems in all accommodation and service spaces, stairway enclosures, and corridors; requirements concerning emergency lighting, general emergency alarm systems and other means of communication; requirements for additional fireman's outfits; requirements for portable foam applicators of the inductor type; and requirements for a fixed fire extinguishing system in compliance with Regulation 11-2/7 in machinery spaces of category A. These requirements, which are applied in stages between 1994 and 2010, came to be collectively known as the "retroactive fire safety amendments."

December 1992 Amendments primarily concerned the fire safety of new passenger ships (that is, those built after I October 1994) carrying more than 36 passengers. They made mandatory automatic sprinklers, fire detection and alarm system centralized in a continuously manned remote control station that includes provisions for the remote closing of fire doors and shutting down of ventilation fans. Also included were new standards for the fire integrity of bulkheads and decks along with improvements to standards for corridors and stairways used as a means of escape in case of fire. Emergency lighting to identify escape routes was made mandatory.

1994 Amendments added three new chapters to the SOLAS 74. Chapter IX requires vessels and their operators to meet the requirements of the International Safety Management Code; Chapter X introduces the High Speed Craft Code; and Chapter XI addresses special measures to enhance maritime safety, which include requirements for enhanced surveys on bulk carriers and oil tankers.

June 1996 Amendments, among other items, extensively modified Chapter III of SOLAS 1974. Requirements for marine evacuation systems are included in the revision as are requirements for anti-exposure suits. The requirements for free-fall lifeboats also were thoroughly revised. Additionally, the regulations in Chapter III that dealt with design and approval of lifesaving appliances were removed from Chapter III and put into a separate, mandatory code, the International Lifesaving Appliance Code.

The June 1996 Amendments also require all oil tankers and bulk carriers built on or after July 1, 1998, to have in place an efficient corrosion prevention system in all dedicated seawater ballast tanks.

December 1996 Amendments are notable for the requirement for every tanker to be provided with the means to enable the crew to gain safe access to the bow even in severe weather. The amendments contain extensive revisions to Chapter 11-2, *Construction-Fire Protection, Fire Detection, and Fire Extinction,* and also the adoption of the International Code for Application of Fire Test Procedures (FTP Code).

1997 Amendments added a new chapter to SOLAS 1974, Chapter XII, *Additional Safety Measures for Bulk Carriers.* The effective date of this new chapter is July I, 1999. Regulations 4 and 6 in the chapter require all new bulk carriers of ISO meters and above in length that are of single-side skin construction and that are designed to carry solid bulk cargoes having a density of 1000 kg/m^3 and above to have sufficient stability and strength when loaded to the summer load line to withstand the flooding of anyone cargo hold in all loading conditions and to remain afloat in a satisfactory condition of equilibrium. The aforementioned regulations also require all existing bulk carriers of 150 meters in length and above that are of single-side skin construction and that are designed to carry solid bulk cargoes having a density of 1780 kg/m^3 and above have sufficient stability and strength when loaded to the summer load line to withstand the flooding of the foremost cargo hold in all loading conditions and remain afloat in a satisfactory condition of equilibrium. Other highlights of the new chapter include regulation 3, which lists the implementation schedule of regulations 4 and 6 for existing bulk carriers (constructed before July I, 1999) as well as regulation 9, which contains requirements for existing bulk carriers not capable of complying with the damage stability requirements of regulation 4.2 due to the design configuration of their cargo holds.

1998 Amendments mainly concerned Chapter IV. Among the changes was the requirement that contracting governments ensure that suitable arrangements are in place for registering Global Maritime Distress and Safety System (GMDSS) identities, including ship's call sign and Inmarsat identities, and to make this information available 24 hours a day to rescue coordination centers. Also included was a change to Regulation 15 of Chapter IV that addresses testing intervals for satellite emergency position indicating radio beacons (EPIRBs). They also added a new regulation 18 that, if a ship is properly equipped, it must automatically provide information regarding the ship's position in the event of a distress alert.

1999 Amendments amended Chapter VII to make the International Code for the Safe Carriage of Packaged Irradiated Nuclear Fuel, Plutonium and High-Level Radioactive Wastes on Board Ships (INF Code) mandatory. The INF Code sets out how the material covered by the Code should be carried, including specifications for ships. The INF Code applies to all ships engaged in the carriage of INF cargo regardless of the build date and size, including cargo ships of less than 500 gross tons. The INF Code does not apply to warships, naval auxiliary or other ships used only on government non-commercial service, although it is expected that Administrations will ensure these ships comply with the Code. Specific regulations in the Code cover a number of issues, including: damage stability, fire protection, temperature control of cargo spaces, structural consideration, cargo securing arrangements, electrical supplies, radiological protection equipment and management, training and shipboard emergency plans.

May 2000 Amendments amended Chapter III, regulation 28.2 for helicopter landing areas to require a helicopter landing area only for RO/RO passenger ships. Regulation 28.1 requires all RO/RO passenger ships to be provided with a helicopter pick-up area and existing RO/RO passenger ships were required to comply with this regulation not later than the first periodical survey after 1 July 1997.

December 2000 Amendments were significant and amended a number of chapters. A revised Chapter V (Safety of Navigation) brings in a new mandatory requirement for voyage data recorders (VDRs) to assist in accident investigations. Also included in this chapter was the requirement for ships to be equipped with automatic identification systems (AIS), capable of automatically providing information about the ship to other ships and to coastal authorities. The date by which a ship is required to be equipped with VDR and AIS varies depending on the type of ship and the build date.

Amendments to Chapter X (Safety measures for high-speed craft) make the High-Speed Craft Code 2000 mandatory for new craft, which are those built after 1 July 2002. The original HSC Code will continue to apply to existing high-speed craft. The 2000 HSC incorporates changes to bring it into line with amendments to SOLAS.

A revised Chapter 11-2, *Construction-Fire Protection, Fire Detection and Fire Extinction,* as well as a new International Code for Fire Safety Systems (FSS Code) were adopted. Chapter 11-2 was revised to be clear, concise and user-friendly while incorporating substantial changes introduced in recent years following a number of serious fire casualties. The revised chapter includes seven parts, each including requirements applicable to all or specified ship types, while the Fire Safety Systems (FSS) Code, which is made mandatory under the new chapter, includes detailed specifications for fire safety systems in 15 Chapters.

A new regulation was added to Chapter II-I, *Construction-Structure, Subdivision and Stability, Machinery and Electrical Installations,* that prohibits the new installation of materials that contain asbestos on all ships. There were also amendments to the Code for the Construction and equipment of ships carrying dangerous chemicals in bulk (BCH Code) relating to ship's cargo hoses, tank vent systems, safety equipment, operational requirements and amendments to the Code for the construction and equipment of ships carrying liquefied gases in bulk (GC Code) relating to ship's cargo hoses, personnel protection, and operating requirements.

December 2000 Amendments included changes to a number of chapters in SOLAS. The most significant change was the addition of measures to enhance maritime security on board ships and at ship/port interface areas, which were adopted by a Diplomatic Conference on Maritime Security. These amendments created a new SOLAS Chapter XI-2 (the existing Chapter XI was renumbered to XI-1) dealing specifically with maritime security. The new Chapter XI-2, applies to passenger ships and cargo ships of 500 gross tonnage and upwards, including high speed craft, mO,oile offshore drilling units and port facilities serving such snips engaged on international voyages. It enshrines the International Ship and Port Facilities Security Code (ISPS Code). Part A of this Code is mandatory and part B contains guidance for complying with the mandatory requirements. It confirms the role of the Master in exercising professional judgment over decisions necessary to maintain the security of the ship. It contains other regulations which require all ships to be provided with a ship security alert system, address providing certain information to IMO, provide for the control of ships in port, and specify responsibilities of Companies. The Conference also adopted modifications to Chapter V (Safety of Navigation) for a new and accelerated timetable for the fitting of Automatic Information Systems (AIS). Regulation XI-1I3 was modified to require ships' identification numbers to be permanently marked in a visible place either on the ship's hull or superstructure. A new regulation XI-1I5 requires ships to be issued with a Continuous Synopsis Record, which provides an on-board record of the history of the ship and contains information including the name of the ship, the State whose flag the ship is entitled to fly, the date on which the ship was registered with that State, the ship's identification number, the port at which the ship is registered and the name of the registered owner(s) and their registered address.

In addition to the SOLAS amendments adopted at the Diplomatic Conference, the MSC also adopted amendments to Chapter XII (Additional Safety Measures for Bulk Carriers) by adding two new regulations, XII/I 2 and XII/l 3, to require the fitting of high level alarms and level monitoring systems on all bulk carriers, regardless of date of construction, and to require the means for draining and pumping dry space bilges and ballast tanks for any part forward of the collision bulkhead to be capable of being brought into operation from a readily accessible enclosed space. A new regulation was added to Chapter II-113-6 that requires permanent access to spaces in cargo areas of oil tankers and bulk carriers for the purpose of ensuring these vessels can be properly inspected throughout their lifespan. Associated Technical Provisions for the means of access for inspections are mandatory under this regulation. In Part C of Chapter II-I, a new paragraph was added to regulation 31 to require automation systems to be designed in a manner which ensures that a warning of impending or imminent slowdown or shutdown of the propulsion system is given to the officer in charge of the navigational watch in time to assess navigational circumstances in an emergency. There were also amendments to Chapter 11-2 to reflect earlier action that made the IMDG Code mandatory and Chapter III to require liferafts carried on ro-ro passenger ships to be fitted with a radar transponder in the ratio of one transponder for every four liferafts."

8.3.3 MARPOL Convention

During the early 1900s, various countries introduced measures to control and deter discharges of oil within their coastal waters. Attempts had been made in the mid-1900s for internationally accepted standards for controlling oil pollution, but the World War II interrupted progress prior to an agreement being reached. Based on the growing concern about the amount of oil being transported by sea, the United Kingdom organized an international conference on the subject in 1954. The conference culminated in the adoption of the International Convention for the Prevention of Pollution from Ships (OILPOL Convention), which was transferred to IMO in 1958. The 1954 OILPOL Convention with amendments in 1969 and 1971, prohibited deliberate discharge in *special areas* and within fifty miles from shore, limited operational discharge elsewhere for tankers (15 ppm and 60 liters per nm) and other ship types (100 ppm and 60 liters per nm), and limited the size ofVLCC tanks to provide some oil outflow limits in the vent of collision or grounding.

8.3.3.1 MARPOL 1973

Concerned over the enormous growth of maritime oil transport and the adequacy of the 1954 OILPOL Convention, IMO decided to convene an international conference in 1969. In 1973, an entirely new convention was adopted, which was to enter into force twelve months after receiving ratification from fifteen states constituting 50% of the world gross tonnage. The convention contained administrative articles and five technical annexes. Annexes I and II are mandatory, but the remaining three annexes are optional. The following paragraphs summarize each of the annexes:

Annex I reduced by 50 percent the operational oily discharges to l/30 000 of the cargo. Similarly, it stated that bilges from machinery spaces has to contain less than 100 ppm of oil and could not be discharged within twelve miles from land. Discharge of *oil* was expanded to include sludge, refuse, and refinements, and discharge of oil was completely prohibited in ecologically sensitive *special areas.* Furthermore, equipment requirements were placed on all ships of 400 gross tons and above such that they were required to have oily-water separating equipment. Constraints were also imposed on tankers and their arrangements, thus requiring onboard residue retention facilities, *load-on-top* operations, tank size limits, segregated ballast tank (SBT) arrangements for tankers of 70 000 tonnes deadweight and above, and compliance with side and bottom damage standards.

Annex II contained discharge criteria and measures for control of pollution by noxious liquid substances (NLS) carried in bulk. Substances were divided into four categories according to the hazard they presented to the marine environment, to human health, or amenities. Retention span and toxicity levels were used to categorize over 250 substances. Moreover, the regulations in this annex were weighted based on the substance's category, and they addressed onshore reception, onboard retention facilities, discharge limitations, and tank arrangements.

Annex III (optional annex) addressed ships carrying harmful substances in packaged form, such as containers, portable tanks, and rail tanks. This annex provided requirements for quantity limits, packaging, marking, stowage, and documentation of harmful substances categorized by the International Maritime Dangerous Goods Code (IMDG Code).

Annex IV (optional annex) prohibited sewage discharge within four miles of land unless it was treated by an approved treatment plant. Furthermore, any sewage discharged between four and twelve miles from land must be pulverized and treated prior to discharge.

Annex V (optional annex) provided minimum distances for the discharge of domestic and operational waste, other than those wastes previously addressed by any other annex of the MARPOL Convention. The discharging of plastics is completely prohibited under Annex V of MARPOL.

8.3.3.2 1978 MARPOL protocol

The 1973 MARPOL Convention never entered into force due to technical difficulties associated with implementing Annexes I and II. Because amendments could not be made to a convention that had not entered into force, a protocol was developed. The 1978 MARPOL Protocol, which entered into force in October 1983, absorbed the 1973 MARPOL Convention, while changing the requirements of Annex I and allowing a three-year implementation period for contracting states to solve the technical problems associated with Annex II. Because of this action, the 1978 Protocol and the 1973 MARPOL Conventions are referred to as one treaty: MARPOL 73/78.

The changes made to Annex I by the 1978 Protocol included limits on hypothetical oil outflow requiring segregated ballast tank (SBT) arrangements to protect cargo tanks in the event of collision or grounding for all new tankers of 20 000 tons deadweight and above (previously 70 000 tons deadweight.) Existing tankers allowed the use of crude oil washing (COW) as an alternative to SBT, provided an inert gas system is used during washing operations. A second interim alternative to SBT or COW allowed existing tankers to use dedicated clean ballast tanks (CBT) for two to four years (depending on the vessel's size) after MARPOL 73/78 entered into force. CBT arrangements required the identification of dedicated tanks to solely carry ballast, but transfer of ballast could be made through cargo piping systems.

8.3.3.3 Amendments to MAR POL 73/78

Like the 1974 SOLAS Convention, MARPOL 73/78 has been amended on several occasions. The following paragraphs chronologically highlight the significant amendments, some of which have had a far-reaching impact on shipping.

1984 Amendments affected Annex I of the convention only. The significant changes it imposed included providing oily-water discharge and monitoring equipment provisions to limit or restrict discharges; permitting carriage of ballast in cargo tanks under emergency conditions to ensure adequate strength; reducing slop tank size from 3% of the oil carrying capacity of the ship to 2% under certain conditions; limiting discharge of oily waste from drilling operations to 100 ppm; and strengthening of damage stability requirements to enhance a tanker's survivability.

1985 Amendments recognized that the end of the two-to-four-year grace period for implementing Annex II was nearing and that changes would be needed to facilitate practicable application. These changes included harmonizing survey requirements with Annex I, further restricting the carriage of category Band C substances, requiring pre-washing of cargo tanks, mandating compliance with the International Maritime Dangerous Goods Code (IMDG Code), and mandating compliance with the International Bulk Chemical Code (IBC Code).

1987 Amendments. October 1989 *Amendments, and 1991 Amendments* further defined ecologically sensitive *special areas* under Annexes I and V, respectively.

March 1989 *Amendments* mandated compliance with the Bulk Chemical Code, which is applicable to existing ships, although it was not mandatory under SaLAS 1974. Also, substances listed in Annex II were again updated.

1990 Amendments harmonized survey requirements of MARPOL 73/78 with the SaLAS and Load Line Conventions. These harmonized survey requirements are known as the Harmonized System of Survey and Certification (HSSC). Unlike the latter two conventions, which required a protocol to introduce this harmonization, an amendment under the "tacit" approval regime will enter these MARPOL amendments into force six months after the similar amendments (protocols) to the SaLAS and Load Line Conventions enter into force.

199 J Amendments now require that in the event of failure of the oil discharge monitoring and control system, the defective unit shall be made operable as soon as possible. These amendments also prohibit any piping to and from the sludge tanks to have any direct connection overboard other than the standard discharge connection. Finally, these amendments require ships (oil tankers of 150 gross tons and above and other ships of 400 gross tons and above) to have a Shipboard Oil Pollution emergency Plan (SOPEP) on board, and they revised the format of the Oil Record Book.

1992 Amendments added new regulations 13F and 13G to Annex I. These regulations are perhaps the most significant changes to MARPOL 73/78 yet.

The first new regulation, 13F, applies to new tankers, as defined by these amendments. New tankers of 5000 tons deadweight and above must be fitted with either a double-hull or a mid-deck design. Other methods of design and construction of oil tankers may also be accepted as alternatives to the aforementioned designs, provided that such methods ensure at least the same level of protection against oil pollution in the event of collision or stranding and are approved by the committee, MEPC.

Regulation 13F also sets minimum wing tank widths and minimum double-bottom heights that are dependent on the tanker's deadweight. With some minor exceptions for short lengths of piping, this regulation also prohibits ballast and other piping, such as sounding and vent piping to ballast tanks, from passing through cargo tanks and prohibits cargo piping and similar piping to cargo tanks from passing through ballast tanks.

The requirements ofregulation 13G, effective July 6, 1995, apply to crude oil tankers of 20000 tons deadweight and above and to product carriers of 30 000 tons deadweight and above. Non-segregated ballast tankers must either comply with the requirements of regulations 13F not later than twenty-five years after their delivery date or be phased out. An additional five years or operation may be gained if the vessel has SBT and COW or 30% of the cargo block is protected with wing tanks or double-bottom spaces that are not used for the carriage of oil.

Again, other structural or operational arrangements may be accepted as an alternative to the double-hull requirements, provided such arrangements ensure at least the same level of protection against oil pollution in the event of collision or stranding and are approved by the flag administration.

Finally, Regulation 13G requires an enhanced program of inspection during special, intermediate, and annual surveys to be implemented. An oil tanker over five years old to which this regulation applies shall have on board a complete file of survey reports, scantling gaugings, a statement of structural work carried out, and a structural condition evaluation report.

As can be seen from the above discussion, the 1992 Amendments will have a profound effect on tanker design and construction, and especially on existing tankers in the years to come.

1996 Amendments concerned the provisions for reporting incidents involving harmful substances contained in Protocol I to the Convention. The amendments included more precise requirements for the sending of such reports. Other amendments brought requirements in MARPOL concerning the IBC and BCH Codes into line with SaLAS amendments.

1997 Protocol formed a new annex to the Convention, Annex VI, *Air Pollution from Ships.* The amendments include requirements for fuel oil quality, use/discharge of ozone depleting substances, machinery discharges of nitrogen and sulfur oxides, incinerator discharges, and reception facilities. Annex VI will enter into force 12 months after being accepted by at least 15 states with not less than 50% of world merchant shipping tonnage. As of September 2001, only three states have accepted this Annex. IMO's Marine Environment Protection Committee (MEPC) has been tasked to identify any impediments to entry into force of the Protocol, if the conditions for entry into force have not been met by 31 December 2002.

1997 Amendments addressed concerns over oil pollution from persistent oils, which are considered as severe as those involving crude oil. Consequently, regulations applicable to crude oil tankers were also applied to tankers carrying persistent oils. Related amendments to the Supplement of the IOPP (International Oil Pollution Prevention) Certificate, covering in particular oil separating/filtering equipment and retention and disposal of oil residues were also adopted. A third amendment was to Annex II of MARPOL by adding a new regulation 16 that requires a shipboard marine pollution emergency plan for noxious liquid substances.

2001 Amendments reflect a heightened worldwide concern over oil pollution from single hull tankers due to the ERIKA sinking off the coast of France. The amendments to Annex I established a new global timetable for accelerating the phase-out of single-hull oil tankers resulting in most single-hull oil tankers eliminated by 2015 or earlier. Although the new phase-out timetable sets 2015 as the principal cut-off date for all single-hull tankers, a flag state may allow for some newer single hull ships registered in its country that conform to certain technical specifications to continue trading until the 25th anniversary of their delivery. However, any Port State can deny entry of those single hull tankers that are allowed to operate until their 25th anniversary and they must communicate their intention to do this to IMO. The revised regulation also identify three categories of tankers:

Category 1: An oil tanker of 20 000 tonnes deadweight and above carrying crude oil, fuel oil, heavy diesel oil or lubricating oil as cargo, and of 30 000 tonnes deadweight and above carrying other oils, which do not comply with the requirements for protectively located segregated ballast tanks (commonly known as Pre-MARPOL tankers).

Category 2: An oil tankerof20 000 tonnes deadweight and above carrying crude oil, fuel oil, heavy diesel oil or lubricating oil as cargo, and of 30 000 tonnes deadweight and above carrying other oils, which do comply with the protectively located segregated ballast tank requirements (MARPOL tankers).

Category 3: An oil tanker of 5000 tonnes deadweight and above but less than the tonnage specified for Category 1 and 2 tankers.

At the same time these amendments were adopted, the IMO also passed a resolution adopting the Condition Assessment Scheme (CAS) and as an additional precautionary measure, a CAS must be applied to all Category 1 vessels continuing to trade after 2005 and all Category 2 vessels after 2010. Although CAS does not specify structural standards in excess of the provisions of other IMO conventions, codes and recommendations, it provides for more stringent and transparent verification of the reported structural condition of the ship and that documentary and survey procedures have been properly carried out and completed. The Scheme also requires that compliance with the CAS is assessed during the Enhanced Survey Program of Inspections concurrent with intermediate or renewal surveys currently required by resolution A.744(18).

8.3.4 International Convention on Load Lines

In 1875, English legislation passed a requirement that a mark be placed on the vessel's side to prevent overloading. As accident investigations came under increased scrutiny and monitoring, underwriters and the Lloyd's Register of Shipping became concerned with issues such as reserve buoyancy, watertight integrity, hull strength, stability, and safe working conditions on deck for the crew. Subsequently, two governments (British and German) established rules embracing these principles. Other maritime nations soon adopted their own sets of similar standards. Britain, seeing the increase of international trade during the early 1900s, invited maritime governments to participate in a conference to develop international standards for all vessels operating internationally. However, due to World War I, the conference's objectives were not met until 1930, which saw the completion of the first International Convention on Load

Lines, 1930 (ICLL). The concerns previously mentioned were covered by this convention and served the maritime industry for thirty-eight years. Taking advantage of IMO's wealth of international and technical expertise concerning marine safety, which was not available during development of the 1930 ICLL, maritime governments set goals to develop a new convention on load lines to consider the almost four decades of technological advances that had occurred in the marine industry. This culminated in the development of the 1966 ICLL under the management of IMO.

8.3.4.1 1966 International convention on load lines

Three areas can categorize the principal provisions of the 1966 ICLL: survey requirements, conditions of assignment, and minimum geometric freeboard.

The survey requirements included in the convention, which call for initial, annual, and renewal surveys, ensure that the vessel's structure, fittings, and appliances, as addressed by the convention, are maintained in an effective condition. Furthermore, the convention issued the conditions of assignment that must be met prior to the vessel being assigned a freeboard and issued a Load Line Certificate to embody the following areas: master's information, weather tight integrity, and protection of the crew.

Information to be supplied to the master consists of a loading manual to assess the vessel's stresses and longitudinal bending moments as well as a trim and stability booklet that assesses the stability of the vessel for various loading conditions. Weather-tight integrity provisions address the closing arrangements, minimum sill heights, and structural integrity of the closure for ventilators, air pipes, companionways, hatches, scuppers, and other openings that penetrate the hull and provide possible sources of water ingress. Lastly, protection of crew addresses requirements necessary to ensure safe passage of the crew about the main deck. These requirements include location, spacing and height of guardrails, gangways, and lifelines. Requirements for sufficient accessibility to crew accommodations also are addressed.

A major part of the ICLL is the regulations to determine the minimum geometric freeboard for a vessel. The criteria is empirically based considering several geometric and hydrostatic parameters of the vessel relative to providing sufficient reserve buoyancy to resist capsizing and alleviating the buildup of water on deck to minimize the potential for water ingress. These requirements have remained intact since their inception. Yet, there is movement at IMO by some members to reconsider the requirements comprising the minimum geometric freeboard and perhaps use analytical simulations and model tests to determine the vessel's seaworthiness (in terms of water on deck for certain sea conditions). Given the other convention's (SOLAS 1974) requirements that address water ingress and sufficient amounts of reserve stability in terms of intact stability and subdivision requirements, the objectives of the minimum geometric freeboard may also be satisfied by a more realistic assessment of the vessel's stability characteristics. This is presently seen in IMO's development of dynamic-motion-response-based guidelines that assess the amount of water shipped for containerships without hatch covers.

8.3.4.2 Amendments to the 1966 convention on load lines

The 1966 ICLL has not been amended which is, in part, due to fact that the ICLL can only be amended through the positive acceptance process. Amendments can be considered by the Maritime Safety Committee, the IMO Assembly or by a Conference of Governments; however, the amendments can only come into force 12 months after being accepted by two thirds of Contracting Parties to IMO. In practice, this has resulted in amendments that were adopted in 1971, 1975. 1979, 1983 and 1995 never receiving the necessary acceptances to enter into force.

1988 Protocol was adopted primarily in order to harmonize the Convention's survey and certification requirement with those contained in SOLAS and MARPOL 73/78. All three instruments require the issuing of certificates to show that requirements have been met and this has to be done by means of a survey that can involve the ship being out of service. The harmonized system alleviates the problems caused by survey dates and intervals between surveys, which do not coincide, so that a ship should no longer have to go into port or repair yard for a survey required by one Convention shortly after doing the same thing in connection with another instrument. Unlike the ICLL, the 1988 Protocol can be amended through the tacit approval process.

Revision of the 19661CLL, as amended by the 1988 Protocol, is currently being done by IMO's Sub-Committee on Stability, Load lines and Fishing Vessel Safety (SLF). The revision is focusing on wave loads and permissible strengths of hatch covers for bulk carriers and other ship types. The first draft of a revised Load Line Convention is expected to be presented to the Maritime Safety Committee in 2002.

8.3.5 Tonnage Convention

Virtually all flag states require that before a ship is registered, it must be measured in accordance with its national tonnage regulations to ascertain gross and net tonnage. Determination of a vessel's tonnage is necessary since the figures are used to determine the applicability of international and national regulations, port fee charges, manning requirements, and ship's identification.

Existing national tonnage regulations were derived from the British Moorsom System of tonnage measurement which dates back to the British Merchant Shipping Act of 1854. As many maritime states adopted this measurement system, conflicting interpretations and amendments unique to individual states led to considerable differences worldwide in its application. Reciprocal agreements among some maritime states alleviated some of the differences but not all. Consequently, various attempts were made to standardize a system of tonnage measurement that could be used by all maritime states. The need for a fair international tonnage measurement system was evidenced by the fact that under various national rules exempted and deducted spaces are treated differently. For example, small ships of identical size and form could vary from 200 gross tons to as much as 1000 gross tons. The variations in tonnages caused inequities in the assessment of charges and in the application of provisions of treaties and laws.

The League of Nations initiated studies on the unification of tonnage measurement systems as early as 1925 and a draft convention with regulations was drawn up in 1939. A conference to consider the draft regulations was postponed until after the end of World War II and the regulations were adopted on June 10, 1947 at Oslo, Norway. The Oslo Convention came into force December 30, 1954. The Oslo Convention afforded a degree of uniformity in tonnage measurement among its adherents. However, a provision requiring unanimous acceptance of any amendments to this convention made it necessary for the adherents to follow recommendations which lacked the force of regulations. In spite of this work, there still remained many differences between the different national systems that needed to be resolved

8.3.5.1 1969 tonnage convention

The Transport and Communications Commission of the United Nations addressed the issue of tonnage measurement. After IMCO came into being in 1958, it tookover the task of developing a universal system of tonnage measurement of ships. Against this background, IMCO formed a subcommittee of its Maritime Safety Committee in 1959 to study the problem and to draw up recommendations for a tonnage measurement system suitable for worldwide application. The intent was to develop a system, which would be just and equitable between the individual ships and ship types, would not hamper ship design or seaworthiness and would take general account of the economics of the shipping industry.

Over a period of years, the subcommittee and its working group considered a number of proposals for a universal system of tonnage measurement. Finally, the International Conference on Tonnage Measurement of Ships, 1969, was held in London during a four-week period beginning May 27, 1969. In seeking a universal system, the Conference decided to eliminate the system of exemptions and deductions from gross tonnage. Moreover, the Conference adopted a formula that would yield gross tonnage closely approximating those of vessels measured under existing national rules without exemptions for shelter tweendecks, deck spaces associated with tonnage openings, passenger spaces, and water ballast spaces. On the other hand, the Conference decided to maintain the net tonnage advantage enjoyed by shelter deck vessels and to extend that advantage to other vessel types having low draft to depth ratios. As a result, some charging authorities shifted their assessment basis from net tonnage to gross tonnage.

The Conference adopted the International Convention on Tonnage Measurement of Ships, 1969 (the Convention), which the delegations felt largely met the intended criteria for a satisfactory system. On July 22, 1980, the Secretary General of IMO announced that Japan accepted on July 17 and consequently, the Convention entered into force on July 18, 1982.

The Convention applies to vessels, except warships, of nations that are:

- party to the Convention,
- 25 m and greater in length, and
- engaged on international voyages.

For these vessels, an International Tonnage Certificate (1969), showing the gross and net Convention tonnage assigned to the vessel, must be carried.

8.3.5.2 Particulars ofthe 1969 tonnage convention

Gross tonnage as defined in the Convention is a function of the total volume of all enclosed spaces of the ship. No exemption of enclosed spaces is permitted although there are certain partially enclosed spaces that are excluded. The formula for gross tonnage GT is:

$$GT = K_1 V$$

where V is the total volume of all enclosed spaces in cubic meters and

$$K_1 = 0.2 + 0.02 \log_{10} V.$$

All volumes of enclosed spaces are measured to the inner side of the shell or structural plating in ships constructed of metal and to the outer surface of the shell or to the inner side of structural surfaces in ships constructed of any other material. The volumes of certain fixed hull appendages are included, but the volumes of hull spaces open to the sea may be excluded.

Net tonnage, as defined in the Convention, is primarily a function of the volume of cargo spaces and the number of passengers. The formula for net tonnage NT is:

$$NT = K_2 V_c (4d/3D)^2 + K_3 (N_1 + N_2 / 10)$$

in which:

V_c = total volume of cargo spaces in cubic meters
K_2 = 0.2 + 0.02 log 10 Vc
K3 = 1.25 (GT + 10 000) / 10 000
D = molded depth amidships in meters as defined in Regulation 2
d = molded draft amidships in meters as defined in Regulation 4
N_1 = number of passengers in cabins with not more than eight passengers
N_2 = number of other passengers
$N_1 + N_2$ = total number of passengers the ship is permitted to carry as indicated in the ship's passenger certificate

In applying the formula:

- the factor (4d / 3D)2 shall not be taken as greater than unity,
- the term K_2V/4d / 3D? shall not be taken as less than 0.25 GT, and
- NT shall not be taken as less than 0.30 GT.

The draft to depth ratio permits a reduction of NT for those vessels with high freeboards and in effect maintains the shelter deck or the tonnage mark concept under the national systems. In some vessels with high freeboards, the effect of squaring this ratio is excessive, therefore the NT is not permitted to be less than 0.30 of the GT.

The Tonnage Conference adopted the coefficients Kj, K_2 and K3 in order to produce curves reasonably representing plots of molded volumes against national gross tonnages and of cargo space volumes and numbers of passengers against national net tonnages. The statistical data for those curves were furnished by IMO members during studies held before the Conference.

8.3.5.2 Retention of national tonnages

Much of the resistance to the Convention was from countries representing shipowners or operators of ships utilizing tonnage reduction techniques. Such ships would have higher gross tonnages under the Convention than under their national systems, which would cause them to exceed tonnage thresholds if the Convention replaced the national systems.

In anticipation of such concerns, the Conference established the application provisions of the Convention in Article 3(2). This Article grandfathered vessels built before July 18, 1982 by allowing them to continue to use their nati,dnal tonnages to meet the requirements of the following existing international conventions:

- International Convention for the Safety of Life at Sea (SOLAS),
- International Convention on Standards of Training, Certification and Watch keeping for Seafarers (STCW), and
- International Convention for the Prevention of Pollution from Ships (MARPOL).

As the date approached when the Convention was to come into force, many nations voiced concerns about the impact of applying Convention tonnage in lieu of national tonnage for ships to be constructed in the near future. In response, IMO developed the concept of *interim schemes,* which extended the Convention grandfather provisions to certain categories of vessels that were built between July 18, 1982 and July 18, 1994. IMO Resolutions providing the specifics of the various interim schemes for those treaties are:

- SOLAS: Resolution A.494 (XII) dated November 19, 1981,
- STCW: Resolution A.540 (XIII) dated November 17, 1983, and
- MARPOL: Resolution A.541 (XIII) dated November 17, 1983

Each country party to the Convention is free to deal unilaterally with problems arising from tonnage thresholds relating to national laws and standards. As a long-term solution, countries have raised some of the legal tonnage thresholds or replaced them with other relevant vessel parameters. Also, some countries continue to apply domestic laws and standards based on national tonnage.

In 1986, the United States adopted a measurement system based on the Convention as its primary measurement system for vessels 79 feet and greater in length. This system is called the *convention* measurement system. However, the previous United States national measurement system, called the *regulatory* measurement system, was retained and could be used for both new and old vessels to apply domestic laws.

8.3.5.3 Canal tonnage

Vessels that transit the Panama Canal and the Suez Canal are measured according to the rules of the respective canal authorities, which are referred to as canal rules. Canal authorities find it relatively easy to accommodate their interests and for that reason find it easier to maintain rational tonnage measurement rules. Canal authorities do not have ships in competition with other ships and each time the relevant canal tonnage is used as a basis for assessing transit tolls, the vessel is available for tonnage verification. Therefore, there are comparatively few options to be considered by the designer.

The Suez Canal Authority recognizes and assigns tonnage based on the regulations recommended by the 1873 International Tonnage Commission (Constantinople) for the purpose of assessing Suez Canal tolls and service fees. The Suez Canal tonnage measurement system is based on a variation of the Moorsom system and the unit ton is 100 ft3 or the metric equivalent, 2.83 m^3, and it is generally applied by the Suez Canal Authority to all categories of vessels.

In 1994, the Panama Canal tonnage measurement system was changed from a Moorsom-based system, with the unit ton being equal to 100 ft^3, to a system known as the Panama Canal Universal Measurement System, referred to as the PCIUMS system. The PCIUMS system is very similar to the 1969 Tonnage Convention, in that a vessel's gross tonnage is determined using logarithmic function based on a vessel's volume. Effective on January 1, 1997, a Panama Canal Commission rulemaking required that a portion of a vessel's on-deck container carrying capacity be included in its PCIUMS net tonnage.

Panama Canal tolls and service fees for commercial vessels and naval auxiliaries, such as transports, colliers, hospital and supply ships, are based on the PCIUMS system. However, tolls and fees for *warships,* as defined in Canal regulations, are based on vessel displacement or weight tonnage not volume tonnage.

8.4 NATIONAL REGULATORYREQUIREMENTS

National standards or regulations are developed for three reasons. The first, and most common reason is to address those vessels not covered by the international requirements, i.e., those vessels that only operate in their national waters. A country may choose to develop entirely different standards or incorporate, where possible, the international standards. Second, national regulations are developed to supplement the international regulations that are not felt to be sufficiently prescriptive or leave details of application to the discretion of the administration. This too is not uncommon and it can lead to conflicts between administrations over the interpretation of some elements of the international standards. Last, national regulations are developed when a country feels that the international standards do not provide an adequate level of safety or environmental protection and determine it is necessary to unilaterally apply higher standards to vessels operating in their national waters. Fortunately, except for notable exceptions, this does not often occur since the express purpose of IMO is for the different nations of the world to come to agreement on internationally agreed upon safety and environmental protection standards to which all countries adhere.

8.4.1 United States National Standards

The marine safety and environmental protection standards for the United States are contained in the Code of Federal Regulations (CFR). The development of federal regulations is speci fically provided for in the Administrative Procedures Act, which requires that the public be given notice and the right to comment on any proposed regulation before it becomes final. The U.S. Coast Guard, as the agency responsible for maritime safety and environmental protection, is responsible for developing and maintaining these regulations (see sub-section 8.5.1.4).

The regulations most pertinent to designers and builders of ships are as follows:

Title 46, *Shipping, Parts* 1-199: contains safety requirements within the areas of structure, stability, lifesaving, marine engineering (mechanical and electrical), fire protection (active and passive), and equipment approval.

Title 33, *Navigation and Navigable Waters*, *Parts 151-159 and* 164: contains the pollution prevention and the navigation safety regulations.

When first developed, these regulations established the requirements for U.S. flag vessels, both those that operated solely within the national waters of the U.S. as well as those that operated internationally. In the past, these regulations were generally considered to exceed the international requirements. However, the U.S. recognized the international standards as the appropriate standards for vessels of other nations that called at U.S. ports. In the recent past, many of the international requirements have come to be incorporated into the U.S. national regulations such that for ocean-going vessels, the U.S. and international regulations are considerably harmonized.

There is a specific and notable example where the U.S. has unilaterally applied a standard that exceeds the international standards. These are the double hull requirements for tankers, which were as a result of the Oil Pollution Act of 1990 (OPA 90). In this instance, the U.S. Congress, in reaction the *Exxon Valdez* grounding and resulting oil spill in Prince William Sound passed legislation requiring the phase-out of all single hull tank vessels to be replaced by double hull tank vessels. This was an instance where the U.S. felt the international standards were not sufficient and took the action it deemed necessary to provide an adequate level of environmental protection for U.S. waters. In 1992, the IMO subsequently adopted similar double hull requirements for tankers with two differences;

the phase-out of single hull tank vessels is not as aggressive as under OPA 90 and since IMO determined the mid-deck design was equivalent to the double hull design, a shipowner could opt for it in lieu of the double hull design. To date, no mid-deck designs have ever been built.

In addition to the regulations, there are policy documents that amplify and provide interpretations concerning both vessel designs and vessel inspections. The two most prominent bodies of policy documents are The *Marine Safety Manual* (MSM) and Navigation and Vessel Inspection Circulars (NVIC's).

8.5 REGIONAL AND LOCAL REGULATORY REQUIREMENTS

In addition to international and national standards, a fairly recent development has occurred whereby regional groups of individual nations such as the European Union have begun to use their authority to establish and enforce requirements related to the marine industry. In addition, within the United States, some states have imposed their own requirements on the maritime industry, usually within the environmental protection arena.

8.6 CERTIFICATION AND ENFORCEMENT

As was stated earlier, the IMO has no power of enforcement for the criteria it establishes but must rely on implementation mechanisms of the individual signatory nations. Enforcement is carried out through two separate and distinct elements: the flag state and the port state.

8.6.1 Flag State

Maritime administrations represent the interests of a sovereign state for the purpose of regulating shipping and shipping-related activities. Nations that have a mechanism for registering tonnage, called a registry are commonly referred to as flag states. Hence, the maritime administration of a nation is responsible for determining what regulations apply to vessels in its registry and for effecting inspection and certification of those vessels.

8.6.1.1 Role of flag state

The flag state is responsible for the following:

- developing and determining maritime regulations: Maritime regulations can be of domestic origin (national laws) or international in nature, and their applicability is usually based upon the vessel's size/tonnage or geographical trading areas,
- representing its nation at international maritime fotums: In carrying out this role, the flag administration represents the maritime interests of the nation at such forums as the International Maritime Organization,
- maintaining its registry (e.g., registering vessels): Vessels that qualify for entry are duly registered and documented by the flag state,
- applying regulations to registered tonnage: After vessels are duly registered, the flag state administers applicable regulations to those vessels,
- providing inspection/certification service for registered vessels: The flag state must provide certification services directly for its vessels or delegate the authority for these services to a capable technical body, such as a classification society, and
- acting in accordance with relevant international regulations: The flag state must abide by international agreements to which it is party or signatory. Such agreements may require the flag state to provide an auditing function over its inspection and certificate function as well as compile and share information related to fleet statistics, accident investigations, and interpretations of regulations.

8.6.1.2 Delegation of authority

Most flag states delegate the authority to survey vessels, issue international certificates and certify tonnage to qualified technical bodies. Usually, classification societies are the recipients of such delegations, and this delegation of authority is then recorded in a formal document that spells out the specific responsibilities of both parties. The classification society, as delegated party under such an agreement, is expected to provide timely, professional service, using criteria determined and interpreted by the flag state. The degree of latitude that can be used by a class society as well as reporting obligations are usually contained in the delegation of authority.

8.6.1.3 Flag state relationship with IMO

Of particular interest is the flag state's relationship with the International Maritime Organization (IMO), the body of the United Nations charged with regulating oceangoing tonnage by consensus means. Member states are those flag states that are members ofthe IMO and hence subject to its binding agreements. Nonmember states are those flag states that do not hold membership at IMO but that may follow proceedings as observer states and may voluntarily adopt IMO criteria as part of their maritime regulations. Signatory states are those member states ofIMO who have signed into force IMO conventions and are thus bound by the convention's provisions. Non-signatory states are member or nonmember states of IMO that have not signed IMO instruments placing regulations into force, but have often voluntarily adopted IMO regulations and standards as part of their maritime requirements.

8.6.1.4 United States Coast Guard

As the agency responsible for maritime safety and environmental protection in the United States, the U.S. Coast Guard is responsible for developing and enforcing the relevant statutory and regulatory requirements. The U.S. Coast Guard is generally recognized as one of the premier maritime safety organizations in the world, not only because of its size, but also because of the breadth of its responsibilities and activities. It traces its origin back to the Revenue Cutter Service in 1790, and over the last two centuries has continually broadened its responsibilities as new laws have been created in response to developing national and world issues or as various other governmental entities have been merged with it. The official name of *Coast Guard* was created in 1915. With approximately 40 000 military and civilian employees, the Coast Guard is the largest organization in the U.S. Department of Transportation and exercises the traditional flag and port state responsibilities of the United States.

The certification process of U.S. flag vessels is how the Coast Guard verifies compliance with the applicable safety and environmental protection regulations. This process culminates in the vessel receiving all applicable international certificates and a Coast Guard Certificate of Inspection.

There are two major components in the certification process; namely a technical review of a vessel's design, and a survey by Coast Guard marine inspectors. During the service life of a vessel, it is subject to periodic inspections and renewal of its certification by the Coast Guard. The technical review of a vessel's design is carried out by the Marine Safety Center (MSC). Marine inspectors stationed at over 40 Marine Safety Offices in the United States carry out vessel surveys. **In** addition, the Coast Guard has marine inspectors in Rotterdam and Japan in order to carry out vessel inspections outside the United States.

Like other countries, the Coast Guard has delegated the authority to issue international certificates along with the commensurate technical review and vessel survey on their behalf under a the Alternate Compliance Program. Under this program, the Coast Guard uses the product of the reviews and surveys done by the classification societies as a basis for issuing the Certificate of Inspection. Prior to receiving authorization to conduct this work on behalf of the Coast Guard, a classification must satisfy certain criteria and enter into an agreement with the Coast Guard. The agreement stipulates the conditions to which the classification society and· the Coast Guard must adhere as well as any supplemental national requirements, which are in addition to international and classification requirements, that the classification society must verify during the review and survey of a vessel. As of April 2003, the Coast Guard had delegated the authority to issue international certificates to the American Bureau of Shipping, Lloyd's Register of Shipping, Det Norske Veritas, and Germanischer Lloyd.

8.6.2 Port State Control

Port state control (PSC) is the inspection of foreign ships in national ports to verify that the condition of the ship and its equipment comply with the requirements of international regulations and that the ship is manned and operated in compliance with these rules. It is a natural and complimentary control to that exercised by the flag state. Many ofIMO's most important technical conventions contain provisions for ships to be inspected when they visit foreign ports to ensure that they meet IMO requirements, as seen by the following list:

- International Convention for the Safety of Life at Sea (SOLAS), 1974, its Protocol of 1978, as amended, and the Protocol of 1988, (SOLAS 74/78/88),
- International Convention for the Prevention of Pollution from Ships, 1973, as modified by the Protocol of 1978, as amended (MARPOL 73/78),
- International Convention on Standards of Training, Certification and Watch keeping for Seafarers 1978, as amended (STCW 78),
- International Convention on Load Lines 1966, as amended, and its 1988 Protocol, (ICLL 66/88), and
- International Convention on Tonnage Measurement of Ships 1969 (TONNAGE 1969).

In recent years, PSC has become more prominent and increased in importance within the maritime safety and pollution prevention regime. Although it is well understood that the ultimate responsibility for implementing and enforcing the provisions of the conventions is left to the flag states, port states are entitled to control foreign ships visiting their own ports to ensure that a minimum level of safety and pollution prevention is maintained within their ports. Because many port states have concluded that shipowners, classification societies and flag state administrations have failed to adequately ensure that ships comply with the requirements of the international maritime conventions they have dramatically increased their port state control programs and increased scrutiny of foreign ships calling in their ports. This has resulted in port state control becoming a more active partner with the flag states to enforce compliance with the international safety and pollution prevention requirements.

When conducting a port state control inspection, the administration may use its own government inspectors or other inspectors (such as class society surveyors) to whom it has delegated authority to act on its behalf. The flag state where the vessel is registered may be notified of such inspections, as may the class society with which the vessel is classed.

Initially, the PSC inspection generally consists of a visit on board to verify that necessary certificates and documents are valid. The initial visit also gives the inspector an opportunity to judge the general appearance and condition of the vessel. When certificates are overdue or expired, or where they appear to be reasons to suspect that the ship and/or its equipment may not be in compliance with the relevant convention standards, a more detailed inspection is usually undertaken to determine whether or not the ship is in compliance with the international requirements. In addition, grounds for carrying out a detailed inspection may consist of one or a combination of the following: a report or notification from another authority; report or complaint from the master, a crew member (or any person or organization with a legitimate interest in the safe operation of the ship or in the prevention of pollution); or the finding of deficiencies during the inspection.

During an inspection, if deficiencies are found that affect safety, health, or the environment, the port authorities will ensure that the deficiencies are rectified before the ship is allowed to proceed to sea. If necessary, they will sometimes detain the ship for that purpose, notifying the flag state of the action taken. Additionally, differences of opinion as to the interpretation of international regulations may develop. In such instances, the flag state where the vessel is registered should be consulted for their interpretation of any applicable requirement.

8.6.2.1 PSC memorandums of understanding

PSC inspections were originally intended to be a back up to flag state implementation, but, as just noted, experience has shown that they are extremely effective in reducing substandard ships. However, instituting a PSC program involves creating an administration, a team of surveyors and inspectors, which can be expensive. By combining with other countries to form regional PSC agreement these costs can be reduced and the effectiveness of the inspection program increased. There are a number of other advantages. A ship going to a port in one country will normally visit other countries in the region before embarking on its return voyage and it is to everybody's advantage if inspections are coordinated to ensure that as many ships as possible are inspected but at the same time individual ships are prevented from delay by unnecessary inspections. In addition, the data collected can help to target flags, companies and individual ship that have poor safety records. \.

The first regional agreement was created in Western Europe in 1982 by means of the *Paris Memorandum of Understanding on Port State Control,* commonly referred to as the Paris MOU. IMO, in 1991 adopted Resolution A.682(17) *Regional Cooperation in the Control of Ships and Discharges,* to promote the establishment of other regimes in the various regions of the world following the pattern adopted by the European region through the Paris MOU. Since then, other regions have adopted PSC MOUs and as of2001, the following regional MOUs exist:

- Paris MOU (Europe and North Atlantic region including Canada),
- Acuerdo d Vina del Mar (Latin American region),
- Tokyo MOU (Asia-Pacific region),
- Caribbean MOU (Caribbean region),
- Mediterranean MOU (Mediterranean region),
- Indian Ocean MOU (Indian Ocean region),
- Abuja MOU (West and Central African region), and
- Black Sea MOU (Black Sea region).

The United States has an active and aggressive PSC program. While not a member or participant in any regional MOU, because of the number of foreign ships calling at its ports, the United States has had a significant impact on PSC activities worldwide. Additionally, as part of its PSC program, the United States, initiated QUALSHIP 21. QUALSHIP 21 is a program that recognizes and rewards ships that over time have demonstrated full and complete compliance with the international safety and pollution prevention standards.

There is one additional MOU that has and will continue to have impact within the various PSC programs and that is the European Quality Ship Information System (EQUASIS) MOU. EQUASIS was established in May 2000 for the purpose of making merchant ship information available to maritime organizations. The information is provided by the Paris MOU, Tokyo MOU, United States, lACS Classification Societies, and P&I Clubs members of the International Group of P&I Clubs. It includes the following items: ship particulars (IMO number, name, flag, type, gross tonnage, etc), classification society, information on Safety Management Certificate (SMC), P&I club covering the ship and port state control inspections (list of inspections and detentions, summaries of deficiencies for each inspection, deficiencies that led to detention). Clearly, making this information transparent is important in the world maritime community's efforts to reduce substandard ships.

Chapter 9

Contracts and Specifications

Kenneth W Fisher

9.1 INTRODUCTION TO SHIPBUilDING CONTRACTS

9.1.1 Decisions Required for a Shipbuilding Contract

A contract for the construction of one or more vessels is the logical outcome of a decision by a shipowner to acquire the new shipes) to further the objectives of the organization. Possible objectives include: a favorable return on investment; a public service (ferries, search and rescue, etc.); a *captive* transportation link as a component in a larger logistics system; a military or security capability; environmental monitoring and preservation; scientific research; and recreation (cruise vessels and large yachts); among other objectives of ship owning organizations.

Once the decision to acquire the new ship is made, multiple follow-on decisions are necessary. Many of those decisions are reflected in the technical specifications and plans, or drawings, which define the physical ship that will satisfy the requirements of the shipowner. The development of those technical requirements in the form of Contract Specifications and Contract Plans is discussed at length in Section 9.3.

However, many non-technical decisions are needed also (see Chapters 4 and 10). Some of the non-technical decision involve selecting a naval architectural firm to develop the technical requirements; the extent to which the design will be developed by the shipowner; the identification of qualified shipyards that will be invited to submit bids or proposals; the format of the request for proposals or invitation to bid; the flag of registry for the completed ship; and the classification organization that will be involved during design development and construction. In addition to those decisions, the shipowner's organization must select:

- the means of financing the construction of the ship,
- the means of financing the mortgage for the completed ship,
- the basis of comparison of offers or bids from several shipbuilders,
- a shipbuilder from among the responsive bidders,
- the format of the shipbuilding contract, and
- other non-technical decisions that need to be made just to initiate the acquisition process.

There are *hazards* associated with each such non-technical decision, which hazards are in the form of risks associated with the relevant experience of the naval architect, the locale of the shipbuilder, the applicable law, financial guarantees, and the relevant experience of the shipowner's staff that is managing the ship acquisition process, among other factors. The process of developing the contract for ship construction and the letting of the contract by the shipowner is, accordingly, an orderly sequence of risk evaluation at each step along the way, followed by action that minimizes the relevant risks or considers other factors if a slightly greater risk is found acceptable.

For example, from a shipowner's perspective, retaining a naval architectural firm that has designed many similar vessels may present a lesser risk than utilizing the services of one that has only designed other forms of vessels, though the risk differential may be minimal. An adverse outcome of such risk may be the need to negotiate a Change Order to achieve a partial rearrangement of several items to enhance operating efficiency, based on the operator's experience, which experience was not appreciated by the naval architects for whom this was their initial design of this ship type. If the shipyard is accomplishing that level of design, the shipowner may be similarly concerned about the experience of the shipyard's design staff.

The decision as to how much of the design is to be developed by the shipowner's naval architects and design engineers, and how much design development responsibility is to be assigned to the shipyard, is an important one. For certain vessel types, such as tankers and bulk carriers, shipyards may offer standard designs at attractive prices. Shipowners must recognize that such standard designs are generally optimized from the shipyard's production perspective, and may not result in the best operational, economic and maintenance considerations from the shipowner's perspective.

The considerations and processes leading to those non-technical decisions are almost always unique to each ship owning organization, thus precluding the possibility of a comprehensive discussion of them. Consequently, while this chapter will occasionally refer to the outcome of most of those non-technical decisions, with one exception, they are not a point of focus within this chapter. The exception to those non-discussed, non-technical decisions is the last one mentioned, the format of the shipbuilding contract. This subject is thoroughly discussed in Section 9. 2.

9.1.2 Learning from Experience

A new ship for most ship owning organizations is just one more in a series of vessels in its possession, but sometimes an acquisition of a new ship is a *first* for an organization that is just getting into ship owning. Initially, it would appear that ship-owning organizations that previously have acquired ships possess the experience to undertake the acquisition process without difficulty due to that previous experience. Conversely, it would appear that first-time ship owning organizations likely would encounter greater difficulties due to the lack of relevant experience. However, neither of those statements is necessarily true.

The only experience a ship owning organization can bring into a ship acquisition process is that of the individuals involved on behalf of that organization. If there has been a turnover of personnel since the last several acquisitions, all of the *learning* that came into the organization through those acquisitions was lost to that organization if key personnel departed. In other words, there is no *corporate memory* unless there is no turnover of key personnel or if that experience has been translated into documentation that is used for each subsequent ship acquisition. However, such documentation is a rarity in the marine industry, with the notable exception of large government agencies having numerous documented procedures and sub-procedures. But even if acquisition guidelines and procedures are documented, they still have to be implemented by the Purchaser's staff, which implementation may result in new interpretations of the same procedurallanguage.

Similarly, it can be appreciated that a first-time shipowner can, in fact, have the benefit of prior ship acquisition experience by using, as employees or consultants, persons having directly relevant experience. It is important to stress the word *relevant,* since non-relevant experience is often the basis of false confidence or misunderstandings, leading to difficulties in the ship acquisition process. Some ship owning organizations have occasionally used persons from other industries to oversee a ship acquisition process, leading to difficulties arising from the significant disparities between procedures and expectations between the different industries.

The same perspective is also valid for shipyards; the persons involved in the development and negotiation of shipbuilding contracts on behalf of the shipyard can unwittingly create situations which are more likely to lead to contractual difficulties if the experience of past contracts is not adequately translated into the new contract development process. For example, a shipyard having considerable catamaran-building experience contracted to construct a SWATH-type vessel using estimates based on its prior twin-hull experience. However, due to width restrictions at the waterline, the SWATH construction was far more costly than comparably sized catamaran vessels.

The Chief Executive of the Royal Institution of Naval Architects in 1998-2003, Mr. Trevor Blakeley, introduced that organization's biannual courses on the management of shipbuilding contracts by stating this:

"We have all heard of disasters involving ships, ships that have run aground, broken in half in severe storms, impacted vehicular bridges in fog, or even experienced fires. But there is *another form of disaster involving ships; namely, contractual disasters, situations in which the shipyard and shipowner are both terribly harmed due to mismanagement of the shipbuilding contract."*

The primary basis of this chapter is past experience, not a theoretical approach to the development of contracts, agreements, specifications and plans. The avoidance of the second type of ship disasters, *contractual disasters,* is the educational intent of this chapter. Thus, in a sense, it is a form of documentation of lessons learned from prior experience in the development and management of shipbuilding contracts.

9.1.3 Perspectives, Not Standards

It is recognized that some persons reading this chapter may interpret it as establishing a *standard* for appropriate shipbuilding Agreements, Specifications, Plans and contract managerial duties for ship construction. It is not intended that this chapter establish such standards. This chapter is for instructional purposes only, intended for those persons who do not yet possess experience sufficient to make the decisions that are needed in contract formation and management. The fact that in actual practice an organization may not adhere to the ideas and perspectives set forth below is not necessarily an indication of inadequate contracting and management. Rather, the ideas and perspectives presented in this chapter are intended to bring to light various possibilities and lessons learned in both contract development and contract management. The relevant experience and qualifications of each party's contract management team, coupled with the specific nature of the project, and influenced by market, financial, regulatory and classification factors, may singularly or collectively be superior factors, relative to this chapter's recommendations, for the establishment of an appropriate contract and form of contract management.

9.1.4 Contract Development and Management

There are three aspects of shipbuilding contracts and specifications that are relevant to the context of this book and which also are central to the interests of technically-oriented persons who are likely readers of this book: 1. formation of the agreement - the keystone of the contract; 2. formation of the specifications and plans - the key technical components; and 3. management of the contract during ship construction.

Each of those three key areas is addressed as sections, below. Prior to considering them, however, some fundamental understandings of shipbuilding contracts are reviewed. It will be seen, the title of this chapter not withstanding, that specifications are just one of several parts of a shipbuilding contract. The word "specifications" is included in the title of this chapter to emphasize that this chapter is not a discourse on contracts that is suitable for the legal profession; rather, it is specially intended for project personnel other than attorneys.

Reference 1 is a treatise on shipbuilding contracts that addresses legal issues. Per the Foreword of it, the purpose is to *"present the law relating to shipbuilding contracts in as wide a perspective as possible."* It was initially compiled by a sub-committee of the Assembly of the Comite Maritime International, and subsequently edited into a uniform format by Malcolm A. Clarke, Ph.D., Fellow of St. John's College, Cambridge. The book addresses matters of financial security, title, risks and insurance, default and termination, among other non-technical subjects.

9.1.5 Contracts and Technical Managers

While this chapter focuses on new ship construction, nearly all the elements of it are also applicable to major ship conversion projects, and many of its elements are also pertinent to ship repair. Agreements and Specifications for both ship conversion and ship repair will need to be supplemented by other elements not described in this chapter, and some of the elements described herein would have to be deleted. The reason for the inclusion of this chapter in an otherwise technical book is that the contract is the mechanism that conveys the technical, as well as non-technical, understandings, obligations, rights and responsibilities between the shipowner (or *Purchaser)* and the constructing shipyard (or *Contractor).*

The contract is the instrument that allows the intangible product of the designing naval architects and marine engineers to become a reality; without a contract, the design would never be translated into a tangible object.

Some vessels have been constructed, it may be said by others, without a contract. What is really meant, however, is that the vessel was constructed in accordance with an oral contract, not a written one. While this is altogether possible, it means that the risks associated with the vessel construction were not addressed, so both parties were taking great risks over financial and technical aspects, hoping that the outcome would be satisfactory, but having no written commitment to that objective from the other party. Thus, there is always a contract, but in some rare circumstances it may have been an oral one, not a written one.

It is essential that technical project personnel have overall responsibility for the development and implementation of a shipbuilding contract, rather than business managers or lawyers, since the ultimate purpose of a shipbuilding contract is to develop and deliver a technical object, not to develop temporary business or legal relationships. Each of those, temporary business and legal relationships, are a necessity, but are not a sufficient mechanism for achieving the delivery of a new ship from Contractor to Purchaser. Further, in addition to the technical personnel and the lawyers, a wide range of professionals within both the shipowner's and the shipyard's organizations occasionally will be referring to the contract, though not managing it on a daily basis. These include persons in the areas of insurance, accounting and finance, among other areas.

In the last section of this chapter, it will be shown that the on-site contract management team is responsible for management of the entire contract, including the Agreement as well as the technical requirements. Accordingly, it is important that those technical project personnel who will constitute the contract management team be familiar, if not conversant, with the Agreement to the same extent they are with the technical documents of the contract. Further, in order to ensure that the Agreement gives those technical personnel the rights and responsibilities they need to effectively manage the contract, and assigns to the other contracting party the balance of the responsibilities necessary to achieve the final product (the ship and all its documentation), those technical personnel must participate in the development of the Agreement.

If the technical requirements and technical obligations expressed by the contract are not set forth in a comprehensive document that is entirely suitable for the objectives of the project (developing and delivering a ship), a risk is taken that financial and/or legal issues will control the project, rather than having those issues support but not control the technical project.

This chapter is not a substitute for more detailed education in the areas of contract formation and contract management. It will, however, make the reader alert to the need to look into matters surrounding contract formation and contract management, rather than merely leaving those matters to persons who do not have the same project perspectives that are appropriate to the formation and management of shipbuilding contracts.

9.1.6 Purpose of Shipbuilding Contracts

A shipyard and a shipowner enter into a contract for mutually-beneficial reasons; namely, the shipowner wishes to acquire a ship which is suitable for the shipowner's needs, and the shipyard wishes to construct, for payment, a ship within its shipbuilding capabilities in order to earn a return on its investment in shipbuilding facilities. The shipbuilding contract is the manifestation of those mutual intentions; that is, the purpose of a shipbuilding contract is to achieve the development and delivery of a ship from the shipyard to the shipowner. From the time the parties agree to that technical objective until it is achieved, the parties establish a temporary business relationship, shaped in part by legal obligations and constraints that are intended to produce a satisfactory technical outcome.

More formally, the purpose of a shipbuilding contract is to define the entirety of the temporary relationship between the Contractor and the Purchaser. Essentially, the contract in its entirety establishes the rights, responsibilities, *rules of conduct* and assignment of risks between the two parties pertaining to all foreseeable technical, cost and schedule matters, as well as questions or disputes that may arise between the parties.

The assignment of risks does not end, however, upon contract execution; each Change Order that may b~ executed later as an amendment to the contract also may carry with it risks which must also be assigned. For the Contractor, usually there are the risks of cost and/or schedule overruns for fixed price contracts or fixed price Change Orders; for the Purchaser usually there are the risks of performance of the basic or altered elements of the Contract Work Scope. The assignment of those risks, however, can be different for each of the design and performance parameters and for each subsequent Change Order, as the parties may agree.

The form of a contract determines which party is accepting, to some degree or other, the risk of cost overruns. In the *fixed price* form of contract, the contractor is obliged to complete the ship and the other deliverables all for the contractually-defined fixed price, as may have been supplemented by agreed-upon changes. However, when a new ship type is being created, or when new technologies are being implemented, it may be impracticable for a shipyard to offer a competitive fixed price since there are too many unknowns. In such instances, potential contractors may not be willing to accept the risks of offering a fixed price contract within a range acceptable to the shipowner. In order to obtain the vessel, the shipowner may offer to use a *cost-plus* contract, in which the shipowner will pay all costs incurred by the shipyard, and in which the *plus* payable to the shipyard is determined according to either a formula or a fixed amount per the contract language. It is also possible for the parties to use a contract form, which leads to the sharing of cost overruns. Other variants on contract form are also possible, but infrequently used. The important point is that the form of contract determines how the parties allocate the risks of cost overruns.

9.1.7 Defining Contractual Relationships

Typically, contracts are written documents, which address all, or nearly all, of the potential elements of the contractual relationship. Sometimes, however, the shipbuilding contracts are oral to some extent, with certain elements of the contractual relationship having been established orally, while other components of the same contract may be in writing. It is not uncommon for written contracts to be incomplete; that is, some of the components of the contractual relationship remain undefined at the time the contract is initiated.

If the two contracting parties have mutually decided to not reduce all of the potential components of their contractual relationship to writing, it indicates that they are each taking a risk if an un-addressed aspect of the contractual relationship becomes important at a later time. For example, if a contract requires that the Contractor ensures that the new ship achieve a speed of, say, 28.0 knots, but in fact the vessel can achieve only 26.2 knots, the parties will have to look to the contract to understand what remedies are available to the Purchaser and what rights remain for the Contractor. The Purchaser's remedies may be financial damages or the right to reject the ship; but if the contract did not address what remedies would be available to the Purchaser, neither party can be certain of what will be the outcome of the almost-inevitable litigation. This is addressed further in Section 9.2 in the part on Liquidated Damages (Performance, Design).

As another example, suppose the Purchaser is not forthcoming with several progress payments. If the matter is sufficiently severe and creates a critical cash-flow problem for the Contractor, the Contractor may wish to take some action to minimize the consequences of the lack of contractually defined progress payments. To the extent that the contract addresses the rights of the Contractor under such circumstances, the Contractor has a clear understanding of what can be done to deal with that lack of progress payments. If, however, the contract does not address that potential aspect of the relationship, then there is no predictable outcome to the consequential dispute.

These limited examples are presented to illustrate that many potential aspects of a contract may never have to be defined, but by failing to define those components of the contractual relationship in advance, the parties may have accepted risks. Thus, it can be appreciated that it is preferable to have a contract anticipate and address reasonably potential sources of dispute so that the parties have, in advance, a clear understanding of how they must act in the event a potential dispute arises, and to understand their contractually defined choices in courses of action.

9.1.8 Components of a Contract

The beginning of this chapter listed the three elements of contract support services that are considered herein: Formation of the Agreement; Formation of the Contract Specifications and Plans; and Management of the Contract During Performance. In order to put those three contract support services into context, eight major components of a contract are illustrated in Figure 9.1.

Those components, and possibly some others, as discussed below, constitute the contract. If any component of the contract refers to other standards or other regulations, then those other standards and/or regulations are also part of the contract. The fact that a requirement may be included in a contract by indirect reference does not give it any less validity than a requirement, which is directly identified within, say, the Contract Specifications. For example, suppose a contract requires that the design of a ship achieve compliance with a particular classification organization's *rules.* Suppose, further, that those *rules* refer to the ASTM standards for ship construction, which ASTM standards include minimum dimensions of handrails for inclined ladders. The ship, then, must comply with those minimum handrail dimensions, even though none of the first-level contract documents expressly identify that particular requirement. In other words, all of the standards and regulations are equally binding upon the parties whether directly or indirectly referenced.

9.1.9 Agreement

The Agreement is often miss-labeled as the contract, but as illustrated in Figure 1, the Agreement is only one of the major components of a contract, though it is unique to each particular contract. Because the Agreement is the largely non-technical heart of the set of documents comprising the contract, its formation is addressed separately in Section 9.2. The Agreement should clearly identify each of the other major components of the contract in a non-ambiguous manner, by using author, date of publication, a revision number or other unique identifying number, if applicable.

The Agreement is also the primary document in the hi-

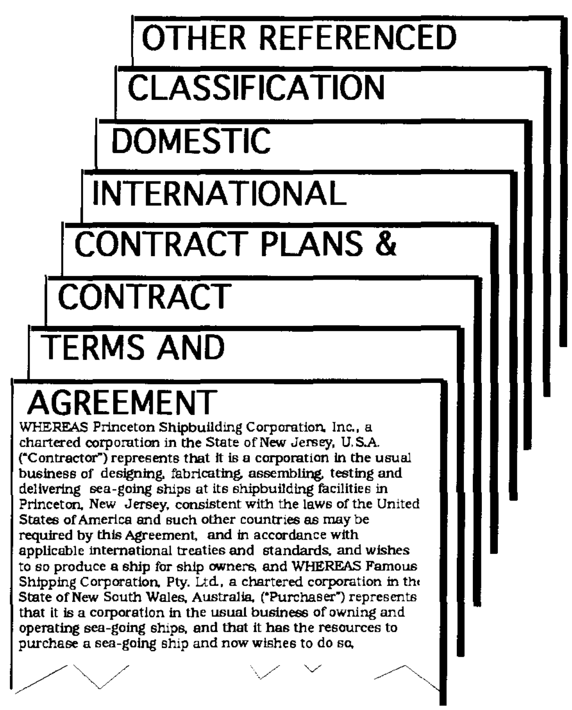

Figure 9.1 Major Components of a Commercial Shipbuilding Contract

erarchicallist of the of components of the contract, with the hierarchy being stated within the Agreement to set an order of precedence in the event of inconsistencies between the various components of the contract. An example table of contents of a commercial shipbuilding Agreement is illustrated in Table 9.1.

Several organizations have standard forms of agreements, but they may refer to them as contracts.

Those forms are the starting points of negotiations and development of the final form of the Agreement. The Association of West European Shipbuilders (AWES), the Shipowners Association of Japan (SAJ), and the Norwegian Shipowners Association (NSA) are among those organizations that have such standard form agreements. **In** the United States, due to significant government involvement in many shipbuilding contracts, the U.S. Maritime Administration has had standard form agreements, too. Of course, major government agencies also have their own forms for acquisition of their own ships.

9.1.10 Contract Specifications and Plans

Two other major contract components are entirely unique to each contract, the Contract Specifications, and the Contract Plans, which may include schematics and diagrams. Because they are entirely unique, they are prepared in advance by one or both of the contracting parties. Often, the Contract Plans are considered to be a subpart of the Contract Specifications, but that is not necessary. Further, if the parties intend that the Contract Plans be superior to the Contract Specifications in legal precedence (hierarchy) of contract components, the Contract Plans cannot be a part of the lower-level Contract Specifications. Because these components of the contract constitute its technical focus, the formation of them is addressed separately in Section 9.3. When a shipyard offers a standard or semi-standard design to a shipowner, these two components of the contract are usually well developed in advance by the shipyard. The shipyard may attach to the specifications a *maker's list* identifying the manufacturer and model number of the equipment items that are to be installed. The shipowner may seek alterations to the shipyard-prepared documents only in selected areas, which are of particular importance to the individual shipowner, such as cargo handling or docking and mooring arrangements. The accommodations areas of otherwise standard ships may also be subject to variation due to the different nationalities of the operating crew. Further, for purposes of fleet standardization, a shipowner may negotiate for particular brand names of equipment components, rather than allow the shipyard to select from among several manufacturers of that equipment.

When the ship is being designed by the shipowner, however, the shipowner's staff, or outside consultancy, develops the Contract Specifications and Contract Plans in advance. Extreme caution should be used by shipowners who allow their staffs to continue developing those Specifications and Plans after the requests for proposals have been issued to bidding shipyards, since subsequent modifications to the Specifications and/or Plans may have a significant impact on the shipyard's price and/or schedule.

TABLE 9.I Commercial Shipbuilding Agreement Typical Section Headings

Introduction
Entire Agreement
Coordination of Contract Documents
Definitions, Abbreviations, Interpretation of Terms
Delivery of Vessels
Options of Additional Vessels
Project Schedule
Scope of Work and Representations
Intellectual Property Rights
Materials and Workmanship
Regulatory and Classification
Industry Standards
Contract price
Unit Price
Delivery of Vessel(s) to Purchaser
Liquidated and Actual Damages (Delivery)
Liquidated Damages (Performance, Design)
Representatives of the Parties
Examination of Plans
Inspection of Workmanship and Materials
Changes in Specifications, Plans and Schedule
Adjustment of Contract Price and Schedule for Change Orders
Extension of Time
Final As-built Drawings and Calculations
Operating and Technical Manuals
Test and Trials
Warrant Deficiencies and Remedies
Progress Payments
Contract Retainage
Special Retainages

Caution should be used when Guidance Plans, or Contract Guidance Plans, are included in the contract documents, as distinct from the Contract Plans themselves. Some shipowners' naval architects add such Guidance Plans to the contract packages because it is intended that those Guidance Plans have a different contractual significance than the Contract Plans. Unless the difference in contractual significance is clearly communicated within the contract package, it is likely that the Purchaser and the Contractor will have differing interpretations as to that significance. A further discussion of this issue, along with other drawing-related issues, is presented in reference 2, as well as Subsection 9.3.24, below.

9.1.11 Non-Unique Components

Four of the components of the contract, as shown in Figure 9.1, are not unique to each contract in any regard, and thus do not require any pre-contractual preparation. They are the International Regulations, the Domestic Regulations, the Classification Requirements, and the Other Referenced Standards. The exact editions, revisions or selections of those components must be unambiguously identified in the Agreement. The inclusion of non-applicable regulations or standards in the contract can be as harmful to contract fulfillment as can be the absence of otherwise necessary regulations or standards in the contract. Periodically, persons who are assembling contract packages should review the initially identified regulations and standards to ensure that they are all the latest versions and that they are applicable to the particular ship which is being acquired at this time.

When distributing copies of the contract package to prospective bidders, it is usually not necessary to copy and distribute the non-unique components of the contract to others. However, bidding shipyards should not hesitate to ask the shipowners for copies of those components of the proposed contract documents that are not already in the possession of the shipyard; bidding a job without having reviewed all of the requirements is a recipe for unexpected costs and schedule impacts. Equally, shipowners' staffs should not list any documents within the contract package unless they have been obtained and reviewed by qualified personnel for applicability, timeliness and general meaningfulness in the contract.

9.1.12 Terms and Conditions

The Terms and Conditions of a contract, none of which are unique to a particular shipbuilding contract, are often standardized by Purchasers, especially if the Purchaser is a governmental agency or commercial entity, which frequently acquires ships, If a term or condition has to be unique to a particular contract, it would probably be best to include it in the Agreement, not in the Terms and Conditions

However, some governmental agencies must select specific provisions from a list of potentially applicable ones. In some contracts, the Terms and Conditions are integrated into the Agreement. In any event, prior to finalizing the form of the contract in its entirety, the Terms and Conditions have to be reviewed to ensure their relevance and applicability to the project. An example table of contents of a commercial shipbuilding contract's Terms and Conditions is illustrated in Table 9.11. If the Terms and Conditions are integrated into the Agreement, the consolidated table of contents of the Agreement would include all of the components of Tables 9.1 and 9.11.When contract packages are being assembled, a review of recent, prior contracts may indicate that certain Terms and Conditions could be adjusted to achieve more-meaningful compliance or easier-to-understand requirements.

9.1.13 Contractor's Technical Proposal

Some shipowners seek technical proposals from bidding shipyards, which proposals show the shipowner how the bidding shipyard's offered ship will satisfy operational and/or performance requirements set forth in the shipowner's request for proposals. If such a procedure has been employed by a shipowner in the process of contract development, the successful bidder"s technical proposal is usually

TABLE 9.11 Commercial Shipbuilding Terms And Conditions

Typical Section Headings	
Care ofVessel(s)	(Purchaser Default)
Access to Vessel(s)	Disputes and Claims
Responsibility for Shipyard Work and Risk of Loss	Consequential Damages
Insurance requirements	Assignment
Responsibilities and Indemnities	Successors in Interest
Contract Security (Performance & Payment Bonds)	Liens
Termination of Work (Contractor Default)	Notices
Termination of Work	Title
	Permits, Licenses and Taxes
	Applicability of Law
	No Waiver of Legal Rights
	Computation of Time

included as a specifically identified component of the contract. It is also listed in the hierarchy of contract documents, but below the other components.

The purpose of including the Contractor" s technical proposal as a component of the contract is to legally bind the Contractor to fulfilling its proposal, but in such a manner as to ensure that the shipowner-developed Specifications and Plans are superior to the technical proposal in the event of an inconsistency between them.

9.1.14 Integrated Contract Package

Project management team members should review all the components of a proposed contract package prior to execution of the contract to ensure that they are applicable to the project, that they are consistent with the project, and that all the components are fully integrated with one another.

Often, organizations have allowed the Agreement to be developed by their legal staffs, and have had the Contract Specifications and Plans developed by their technical staffs. This is not an unreasonable utilization of special skills if it applied only to the Terms and Conditions of the contract.

However, it creates certain risks for both Purchasers and Contractors if that philosophy is applied to formation of the Agreement. It is not unusual to find, after contract execution, that there are inconsistencies between the Agreement, on one hand, and the General Section, or other sections, of the Contract Specifications, on the other.

The hierarchy clause in the Agreement typically will dictate that the Agreement is superior to the Specifications in the event of such an inconsistency, so there is no contractual ambiguity. Thus, in the presence of an inconsistency, the full intent of the Specifications may not have to be fulfilled by the Contractor, thereby leaving Purchaser with a less than complete set of contract deliverables.

In addition to possibly missing out on otherwise anticipated contract deliverables, there is a more significant reason to have the Agreement drafted or controlled by project technical personnel and later reviewed by the legal staff. Namely, such personnel understand what can go wrong or be overlooked during ship construction, and can thus build into the contract several mechanisms to significantly reduce the likelihood of such occurrences. This is discussed in greater detail in Section 9.2 on Formation of the Agreement.

9.1.15 Decision-Making Authority

The contract documents, especially the Contract Specifications and Contract Plans, used in conjunction with the other components of the contract, define certain technical aspects of the ship that will be developed and delivered to the Purchaser by the Contractor. Numerous details, which are not initially defined in the Contract Specifications and Contract Plans, may have to be developed after the contract is executed. The contractual identification of applicable regulations, classification rules and standards will largely shape many of the developmental *micro-design* decisions that need to be made to achieve the completed ship. However, there will also be numerous developmental micro-design decisions that are not controlled by the contractually identified regulations, classification rules and standards.

When the parties executed the shipbuilding contract, the authority to make those decisions was passed from the Purchaser to the Contractor, unless the contract gives the Purchaser some residual decision-making authority. This is unlikely, however; most contracts give that authority exclusively to the Contractor, modified only by the necessity of allowing the Purchaser to review detailed plans before actual ship construction (2). This matter can become a source of disputes; it is discussed in greater detail in the Section 9.3 on Formation of Contract Specifications and Plans.

9.1.16 Government Contracts

The form of contracts issued by government agencies is often different from commercial contracts, but the general nature of the components of them is the same as the commercial contracts discussed herein. There are more forms of government contracts than there are government agencies; many agencies utilize multiple forms of contracts for vanous reasons.

The form and content of contracts from government agencies must comply with the procurement regulations applicable to each particular government agency. Thus, it is expectable to see differences between federal contracts, on one hand, and state or provincial contracts on the other. Some quasi-governmental agencies are also shipowners, such as port and canal authorities; and they may have forms of contracts that are different again.

Even within a federal or national government, different agencies have different procurement regulations applicable to them, and have evolved their own particular forms of contracts to suit those regulations. Within the U.S., for example, contracts for the Army's supply/logistic support ships are different from the contracts issued by the Army's Corps of Engineers, who maintain dredged waterways. The Navy's contracts for combat ships are a different form than those used for auxiliary ships. The National Oceanographic and Atmospheric Administration's contracts for its ships are different from other federal agencies. Coast Guard contracts for its front line cutters are different than for its support ships, such as small search-and-rescue craft.

Non-maritime regulations may affect the forms of contracts from government agencies, such as requirements for minority-owned or women-owned contractors, contracts set aside for small businesses, the need to comply with equal employment opportunity laws, or contracts set aside for economically-depressed areas, among other possible constraints.

Most government contracts are awarded based on either lowest bid or best value bid that fully conforms to the requirements of the contract. The criteria to establish best value vary among the agencies. In contrast, a commercial shipowner has the flexibility to award the contract on any basis it wishes, not necessarily lowest bid or best value.

The administration of government contracts is usually bifurcated; one part of the government agency has technical oversight and responsibility, and another part of the same agency has fiscal oversight and responsibility. This bifurcated contract management means that a contractor has to interact with the government agency, as its customer, in a manner which is different than the way that same contractor would interact with a commercial customer.

When government agencies send out requests for proposals, invitations to bid, or similarly named bid packages, the packages usually include the Agreement and the Terms and Conditions under which the contract will be awarded. The opportunities to negotiate the clauses oftheAgreement or the sections of the Terms and Conditions are more limited than for proposed commercial contracts. Pre-bid questions posed to the government agency may result in a re-examination of parts of the proposed Agreement or Terms and Conditions, but usually the agency will not consider altering those components of the proposed contract due to procurement regulations imposed on the agency.

The administration of a government contract by a commercial shipyard is inevitably more complex, and thus more costly, than administration of a commercial contract. There are multiple reasons for this phenomenon, but experienced shipyards take those extra costs into account when preparing their bids for government contracts.

Despite all those differences between commercial contracts and government contracts, the fundamentals are the same. Whether given different titles or other nomenclature, the components of a government contract are the same as illustrated in Figure 9.1. The purpose of a shipbuilding contract involving a government agency remains the same as described above for commercial contracts: defining the technical aspects of the products to be delivered and establishing the rights, responsibilities, "rules of conduct" and assignment of risks between the two parties pertaining to all foreseeable technical, cost and schedule matters, questions or disputes that may arise between the parties, all for the intended delivery of a ship and the associated documentation.

9.1.17 Government Role in Commercial Contracts

There are several reasons why there may be direct or indi-' rect participation by a government agency in a contract involving a commercial shipowner and a commercial shipyard. One possibility is that the vessel is being constructed for long-term charter to a government agency, so the agency may have technical representatives in the shipyard or examining shipyard drawings in parallel with the commercial Purchaser's representatives. In that situation, while there may be no direct contractual relationship between the government agency and the shipyard, but because it is hard to ignore an *elephant* in your back yard, the management and administration of the contract will be affected.

A more common possibility is that a government agency is providing some form of financial support in order to encourage the domestic shipbuilding industry. That financial support may be in the form of a mortgage guarantee, perhaps predicated on the ship's construction meeting certain criteria.

Another form of governmental financial support may be a direct shipbuilding subsidy, where the agency pays for a certain percentage of each progress payment, again perhaps predicated on the ship's construction meeting certain criteria. A third form of government financial support may be an indirect subsidy, in which the government agency has a relationship with the shipyard in order to help offset some of the shipyard's costs. These last two forms of financial support (subsidies) are, of course, hotly debated within both domestic and international political arenas.

Nevertheless, it should be appreciated that any form of governmental financial assistance, direct or indirect, or other government role in a commercial contract may affect some of the clauses of the Agreement and some of the Terms and Conditions of the contract, and may impact the administration and management of the contract as well. Shipyards must be willing to accept those additional burdens, however, if they wish to be eligible to secure the shipbuilding contract.

9.1.18 Charterer's Role in Contracts

In the previous section, the possibility that a government agency may be the vessel's charterer was included as a potential form of government involvement in a commercial shipbuilding contract. Similarly, a commercial vessel charterer may be involved in a shipbuilding contract in which the Purchaser is a separate corporation.

When a charterer, either commercial or governmental, is present at the shipyard, or otherwise looking over the shoulders of the Purchaser's representatives while the ship is being constructed, certain risks may arise. While the Purchaser has willingly entered into back-to-back contracts, the Contractor's performance under the shipbuilding contract may affect the viability of the charter contract. For example, if a charter requires the new ship to be available for first cargo no later than a certain date, a delay by the shipbuilder may result in cancellation of the charter. This situation has occurred several times, leaving the Contractor and Purchaser to figure out what becomes of the ship, if that situation was not already addressed by the contract.

Another possibility is that the Charterer will seek changes in particular items of equipment or in stateroom arrangements to suit the experience or nationality of the crew. Other changes may be needed to suit the specific ports and docking facilities that will be used.

These situations, and others that may arise due to the involvement of the vessel's charterer during ship construction, usually result in change orders, with the Purchaser being caught in between the needs of both the charterer and the Contractor. In many of those instances, it may be best to have those changes made after ship delivery from the Contractor by a separate, topside contractor instead of a full-service shipyard. A riding crew can accomplish some of the changes so that the vessel is not delayed in its initial positioning voyage. Other forms of solutions to the problems that arise due to the charterer's involvement should also be explored for minimum impact on cost and schedule.

9.2 FORMATION OF THE SHIPBUILDING AGREEMENT

9.2.1 Introduction

Major components of a shipbuilding contract have been illustrated in Figure 1 and discussed above in Section 91. It was pointed out that there might be additional components of a contract, such as the Contractor"s technical proposal. In this subchapter, the elements of the Agreement as listed in Table 9.1 are discussed, including their purpose and, if appropriate, special considerations that should be given to them during formation of the Agreement.

The order or sequence of the components of the Agreement are not important, as long as they tie into each other, do not create variances with one another, and are supported by the other components of the contract without inconsistencies or ambiguities. This presentation assumes that the Terms and Conditions as listed in Table 9.11, mostly legal issues, are a separate component of the contract, although they need not be. Some drafters of contracts, especially commercial shipbuilding contracts, include the terms and conditions in the Agreement.

9.2.2 Contract Oeliverables and Communications

During formation of the Agreement and other components of the contract, a fundamental principle of contract management should be borne in mind:

"Contract management should commence the moment a contract is contemplated, not after it is signed." (3)

The significance of that principle during Agreement formation is that it reminds the parties that any contract rights, obligations, communications or inspections, among other considerations, that either party may wish to be able to exercise during contract performance, have to be *built into* the contract documents from the outset. After the contract is signed, it is too late to ask the other party to give you contract rights that are not already spelled-out in the Agreement or other components of the contract.

Every contract has a set of contract deliverables, in addition to the ship itself. Some of these deliverables may include drawings, correspondence, comments, inspection reports, calculations, test results, and similar documentation. Other deliverables may be spare parts, manuals, or other hardware-related items, in addition to training of vessel operating personnel on the use of ship-specific equipment. It is essential that the parties anticipate what the entire set of contract deliverables is to be prior to contract execution. The creation of each contract deliverable has a cost associated with it; and it is impractical, if not unreasonable, to expect one of the parties to agree to produce a deliverable that was not already included in the contract's work scope. Thus, every form of contract communication and deliverable that will be developed under each party's contract management staff has to be identified in advance of contract execution.

9.2.3 Introduction of Agreement

This component of the Agreement first identifies the parties, their corporate names, the legal form of the organization (corporation, partnership, privately-held, non-profit, state or federal agency, etc.), the jurisdiction of their existence, for example, *incorporated in the State of* , and the nature of their business as it pertains to this particular contract.

This section of the Agreement goes on to describe the nature of the project which is guided and controlled by this Agreement (new ship construction, ship conversion, etc.), and then describes the general role of each party. The principle location of the work is also included, but this does not necessarily bind the Contractor to performing all work at that location.

The role of the Purchaser is, of course, primarily financial, in addition to having certain rights of inspection, drawing review, etc., which rights are spelled out in other parts of the contract documents. The Contractor, of course, will be described as capable of constructing, testing and delivering the vessel. One element of this description, which is often left out, but which is essential, is that the shipyard is obligated to complete the design of the vessel from the status of the design as represented by the other contract documents. Ordinarily, a shipyard will understand that it must produce the detail plans and working drawings, which are necessary to achieve construction of the ship. But often some design development efforts are needed between the Contract Plans and Contract Specifications, on one hand, and the detail plans and working drawings, on the other. This part of the Agreement should mention that the Contractor has responsibility to complete the design, as necessary, thus implying that its engineering and drafting responsibility is not limited only to producing detail plans and working drawings, but begins where the Contract Specifications and Contract Plans leave off.

9.2.4 Entire Agreement

This section of the Agreement reminds the parties that only this Agreement and the other documents to which it refers constitute the binding contract; and that any pre-contract agreements or understandings, whether written or oral, have no standing with regard to this contract. However, it is not quite that simple and straightforward.

First, underlying all contract law are legal requirements that the parties cooperate with each other, and that the parties always take actions to mitigate damages in the face of untoward events, regardless of which party will incur those damages. These underlying legal requirements, among others in different jurisdictions, are binding, though unstated in any commercial contract.

Second, it has to be appreciated that pre-contractual agreements or understandings may, in fact, serve to interpret, but not add to, the current contract, as long as those other agreements and understandings are not in conflict with the current contract. Pre-bid correspondence between bidders and the Purchaser, as well as pre-bid meetings, may form the basis for development of a common interpretation of an otherwise-ambiguous specification requirement. If the contract documents contain an ambiguity that is not resolvable by reference to a component of the contract listed in the hierarchy clause, it may already have been resolved in advance of contract execution, in the form of an *interpretation* or an expression of the *intent of the parties.*

As an example, suppose the contract documents state that the final hull color shall be selected by the shipowner's representative; but during contract negotiations, the parties have already agreed that the shipyard can paint it blue because the shipyard has excess blue paint and is offering a lower price if the blue paint can be used instead of some other, as yet unidentified color. If the parties agreed in writing, in advance of contract execution, that the bid price would be reduced in exchange for acceptance of blue paint, then that pre-contract understanding constitutes a binding interpretation of the contract language, because the contract language does not preclude the color selection being accomplished prior to contract execution. Both parties are benefiting from that pre-contract agreement, and it is not inconsistent with the contract, but rather serves to interpret the otherwise-ambiguous contract language.

Clearly, however, if any pre-contract agreement or understanding, whether written or oral, is in distinct contrast to a contractual requirement, that pre-contract agreement or understanding is of no consequence and has no value in contract interpretation.

9.2.5 Coordination of Contract Documents

This section of the Agreement primarily identifies all of the other components of the contract with the greatest specificity available. Do not state, for example, that the Contract Specifications are *the most-recently revised* edition; rather, identify the authors and give the exact date of that revision because there may be later revisions that are not widely disseminated.

Persons who prepare this section of the Agreement must ensure that all of the identified components of the contract are applicable, current, up-to-date, and easily available to the other party.

Another facet of this section of the Agreement is the hierarchy clause, which states in essence that in the event of an error or inconsistency between different components of the contract, certain identified components shall be superior to the others. The Agreement has to address the possibility that the Contract Specifications may require less than is required by the identified regulations or classification rules. To cover such situations, it is best to state that it does not constitute an inconsistency, but that the Contractor must comply with both of them; the ship shall include the greater of the two sets of requirements.

This section of the Agreement should also state that the inclusion of information in one component of the contract and its absence in another component does not, in fact, constitute an inconsistency or error; rather, it shall be interpreted to be equally present in all components of the contract.

9.2.6 Definitions, Abbreviations, Interpretation of Terms

In order to ensure that there are no misunderstandings of how certain terms or words are intended to be used, it is common to have a section of the Agreement which states the interpretations and definitions that are contractually binding. Typical definitions, interpretations and abbreviations are listed in Table 9.III. Some of the technical definitions may appear in the Contract Specifications instead of the Agreement, which does not present a problem as long as there are, no inconsistencies between the two lists of definitions.

As an example, the word *Install* can be defined to include the requirement that the item of equipment also be *furnished* or *provided* by the Contractor, even if such inclusion may not be apparent in non-contractual language.

Install or *Installation-When the Contract Documents state that the Contractor is to install an item, the Contractor shall be responsible to Furnish the item and for providing all labor, tools, equipment, and material necessary to perform such installation, and for which the Contractor shall at no additional cost to Purchaser:*

- *provide all appropriate structural or other foundations, electrical power, water service, piping, lubrication, lighting, ventilation, operating fluids and other facilities or means required for the installation,*
- *shall effect any and all connections to electrical service, water supply, drains, ventilation, and structural or other foundations, and*
- *shall deliver to Purchaser complete, tested and operable machinery, equipment or systems, including operating fluids.*

Other interpretations, definitions and abbreviations should be considered to ensure that there is no opportunity for misunderstandings between the contracting parties.

9.2.7 Delivery of Vessels, Options for Additional Vessels

This section of the Agreement establishes the Delivery Date ofthe Vessel and the place of delivery. Sometimes the place of delivery is other than at the shipyard in order to address taxes, operational limitations, costs of delivery to the region of intended use, or other factors. In the event a single contract covers the construction and delivery of more than one vessel, it must be clearly addressed within the Agreement. If the number of vessels is fixed but more than one, the construction starting date and the Delivery Date for each will have to be defined. (The price for each additional vessel must also be defined in the section on Contract Price.)

Whether or not the Contractor has to submit separate drawings for the Purchaser's approval for each vessel must be considered and addressed. Sometimes details for sister ships are not the same (they are not identical twins, only sister ships). The parties must agree as to how much variance can exist without calling such variance to the particular attention of the Purchaser, and if there are some areas for which no variance is acceptable.

If there is a minimum number of vessels, with options for additional vessels, the appropriate dates for those option vessels also need to be defined. These other dates would include the dates by which successive options must be exercised by the Purchaser, the official start of construction for each option vessel (as it affects progress payments), the number of days allowed for construction of each option vessel, and the Delivery Date for each option vessel.

9.2.8 Scope of Work and Representations

Usually there are two major aspects to the statement of the Scope of Work, and several lesser ones. The first major seg-

TABLE 9.111 Typical Subjects for Definitions, Interpretations and Abreviations

According to	FCC
ANSI	Furnish
Approval	Good Commercial Shipbuilding Practice
ASHRAE	Guidance Plans
ASME	IEEE
ASTM	Install, Installation
AWS	Or equal
Builder	Owner
Buyer	Owner- furnished Equipment (OFE)
CFR	Owner-furnished Information (OFI)
Classification Organization, Agency or Society	Progress Payments
Compliance with	Provide
Contract	Regulation(s)
Contract Change, Change	Regulatory Body Requirements
Contract Documents	Regulatory Bodies
Contract Drawings,	SOLAS
Contract Plans	Special Retainage
Contract Price	SSPC
Contract Retainage	Surety
Contract Specifications	The Vessel Design
Contract Time, or Contract Period	UL
Contract Work, Work Contractor	USCG
Date of Delivery, Delivery Date	USPHS
Day(s)	Warranty Deficiencies
Documentation	Working Plans, Working Drawings
Excessive Vibration, Noise	
Excessive temperature levels	

ment focuses on the creation of the "hardware" aspects of the ship construction project. It assigns certain responsibilities solely to the Contractor, with Purchaser having no concurrent responsibilities. These include the provision of all engineering, labor, equipment, materials, fuel, lubricants, electricity, energy, machinery, facilities, services and supervision necessary for the completion of the design, the construction, outfitting, completion, testing, delivery and documentation of the Vessel in accordance with the requirements ofthe Contract Documents. It should be clearly stated that Purchaser has no responsibility to provide any engineering, labor, equipment, materials, electricity, energy, machinery, facilities, services or supervision, unless there is some well-defined shipowner-furnished information and/or equipment. Further, it can be stated that Contractor shall be responsible for fuel and lubricants needed for tests, trials and filling of all operating systems and piping upon Delivery, but not for filling of reserve and supply tanks.

The second major segment of the Scope of Work addresses the non-hardware, or documentation, aspects, which are a vital part of the completed ship. This part addresses the necessary and/or requested certifications, documents, booklets, letters, drawings, calculations and other contract data deliverables that are to be provided both during construction and upon Delivery of the Vessel by the Contractor, again at no additional cost to the Purchaser. It is important for shipyards to appreciate that the development and acquisition of this documentation must be carefully budgeted, because it can account for a measurable portion of the total contract price. A list of typical Contractor-provided certifications to be provided with the Vessel is shown in Table 9.IV. Other contract data deliverables are not included in that list (see Table VII in Section 9.3, Specifications, for a suggested list of such documentation).

The secondary aspects of this section of the Agreement can include supplementary requirements for fulfillment of the work scope, such as that all engineering, labor, equipment, materials, fuel, lubricants, electricity, energy, machinery, facilities, services and supervision that may be reasonably inferred from the Contract Documents by professional ship builders/repairers as being required to produce the intended result as contemplated by the Contract Documents shall be supplied by the Contractor, whether or not specifically called for in the Contract Documents, and Purchaser shall not be liable for any increase in Contract Price or Contract Time as a result therefrom. Further, this section of the Agreement can state that any items of design, engineering, purchasing, manufacturing, installing and testing that are necessary to satisfy the Regulatory Body requirements, the Classification requirements, and/or the performance and design criteria shall be incorporated into the Contract Work at no additional cost to Purchaser whether or not they are otherwise indicated in the Contract Specifications and/or Contract Plans. Some Purchasers seek a specific warranty from Contractor, to the effect that Contractor warrants that it has reviewed all ofthe Contract Documents and all other documents and materials which it deems necessary or advisable to determine the nature and scope of the Contract Work and has determined that the Contractor can complete the Contract Work by the Delivery Date, all at no additional cost to the Purchaser. However, this may not be appropriate if the regulatory or classification requirements exceed those of the express language of the Contract Specifications and Contract Plans.

9.2.9 **Intellectual Property Rights**

A sometimes overlooked aspect of contracting is the matter of ownership of the vessel's design or selected aspects

TABLE 9.1V Typical Certifications Provided By Contractor

International Load Line CertificateUSCG certification and documentation
ABS Certificate of Classification, Maltese Cross, Full Ocean Service
Safety of Life at Sea Convention Certificate (SOLAS)
USCG Stability Letter
ABS Stability Booklet and Loading Manual
USCG Approval of ABS Stability Booklet
ABS Certification of all pressurized tanks
USCG Safety Equipment Certificate
FCC Certificate of Radiotelephone
USPHS Certificate of Deratization
USPHS Certificate of Sanitary Construction
ABS Certificate of US Regulatory Tonnage
ABS Certificate of International Tonnage
ABS Certificate of Suez Canal Tonnage
ABS Certificate of Panama Canal Tonnage
Builder's Certificate in customary form
Safety Construction Certificate (SOLAS)
Safety Equipment Certificate (SOLAS)
MARPOL Annex I (SOLAS)
Stability Certificate (IMO)
Equipment Certificates (engine, gensets, pressure tanks and the like as required by Regulatory Bodies

of the vessel's design that are not already controlled by copyright laws and/or patents. Some aspects may be as general as the basic ship design or the hull form, or may be as specific as the design of the computer hardware and software for either the propulsion control system or the dynamic positioning system. Many other aspects of the ship's design may also have been initially developed for this particular vessel, but could be used for other vessels as well.

The Purchaser may expect that it has sole ownership of those intellectual property rights because the Purchaser paid for their development through the contract price. On the other hand, the Contractor may expect that it has sole ownership because it has invested more than the design portion of the contract price into the development of those features. The parties should ensure that these matters are addressed in the Agreement.

Some commercial agreements have stated that the Purchaser owns the title to the Vessel Design, but Contractor can use it for other purchasers provided a royalty fee is paid to the Purchaser for each additional vessel constructed for other purchasers, thus recovering, in part, the portion of the Contract Price for the initial design costs. If a shipyard's subcontractor is involved, this matter may be more complex and difficult to resolve, but it is best addressed in the Agreement, rather than allowing it to become the subject of litigation.

9.2.10 Materials and Workmanship

This section of the Agreement typically sets forth the requirement that all materials, machinery and equipment furnished by the Contractor and incorporated into the vessel shall be new, of current production and currently supported by spare parts available in a designated geographic region. Additionally, the Contractor warrants that all design engineers, workmen, subcontractors and others, engaged by the Contractor in the performance of the Contract Work possess suitable professional skills and are appropriately certificated.

This section usually addresses several other aspects of the materials and workmanship, including, among others, the Purchaser's right to reject, and the Contractor's obligation to correct, at no additional cost, any materials or workmanship whenever found to be defective, or otherwise not in accordance with the requirements of the Contract Documents. If no specific aspects of the Contract Documents provide such a basis for rejection, published industry standards sometimes may be used as a basis for rejection. Note, however, that if Purchaser cannot point to a documented requirement as the basis for such rejection, the materials or workmanship cannot be summarily rejected.

Broad requirements pertaining to the materials and equipment can also be addressed in this section of the Agreement. Some of these may be:

- the flushing of all piping,
- the provision of all working fluids in systems,
- the provision of all fuel for testing,
- the installation of safety guards around rotating and sliding equipment,
- the use of only materials and equipment approved by the designated regulatory or classification organization, and
- the use only of certified welders; among other possibilities.

This section of the Agreement could also state that the failure of the Purchaser to discover any non-conforming materials or workmanship does not constitute a waiver of any contractual rights or requirements.

9.2.11 Regulatory and Classification

The Agreement should state with which particular sets of regulations the design and construction of the ship must comply. These regulations will usually include both domestic and international requirements; domestic because the ship will fly the flag of a particular nation, and international because the ship will be trading with other countries, for which port entry is keyed to compliance with certain international regulations. The Agreement generally does not address, however, matters of financial responsibility for potential environmental damage, training of watch standing crew, or other similar matters which are solely the domain of the ship operator, charterer or shipowner.

The Agreement also should clearly identify under which classification organization the ship is to be classified; and if that classification organization has more than one set of rules, identify the particular rules with which compliance is to be achieved by the Contractor.

These two segments often are then supplemented by the requirement, if it is not an unusual contract, that all engineering, all arrangements for plan approval, all arrangements for inspections and any other requirements of the regulatory agencies and the classification organization are to be carried out by the Contractor, again, at no additional cost to the Purchaser.

If the ship is a newly developed form or will contain innovative technology that has not been previously approved by either or both regulatory agencies and classification organizations, the Purchaser's designers may have to remain involved in the plan approval stage. This serves to complicate matters of schedule, payment of fees, and perhaps even warranties.

Some regulatory agencies have agreements with one or two classification organizations to the effect that the classification organization can perform some of the regulatory approvals. The intent is to streamline the regulatory approval process as well as reduce the workload of the regulatory agency. Purchasers should be aware that sometimes the relevant regulatory agency may not have a regular, working relationship with the nominated classification organization; this may create delays in approvals, likely require additional submittals, at extra cost, and may result in unexpected adjustments to the Contract Plans or Contract Specifications. The Purchaser should investigate and, if necessary, resolve these matters prior to contracting.

As regulatory and classification requirements are often incorporated by reference, the Agreement should address the potential for conflict between the express language of the contract documents, on one hand, and the referenced requirements, on the other. For bidding purposes, the Contractor is allowed to rely on the express language of the contract documents as being consistent with the nominated regulations and classification rules. If, however, the Contractor finds that it has to incorporate a greater content in order to comply with the regulations or classification rules, those extra costs are usually for the Purchaser's account. However, if the express language of the contract documents is silent about certain matters, and the Contractor makes an erroneous assumption for bidding purposes, the Contractor will have to absorb the cost consequences of that erroneous assumption.

These two matters, regulatory and classification are examples of why the Agreement should be developed primarily by the project technical personnel, not the attorneys. Knowledge of classification rules, relevant regulatory agencies, procedures for obtaining their approvals, the existence of working relationships between them, and similar matters, all are essential in the development of the Agreement. If those matters are not addressed with adequate precision, there is a strong likelihood of misunderstandings at a later time.

9.2.12 Industry Standards

Any standards with which compliance is to be achieved in the design and construction of the ship, other than those included within the regulatory requirements and classification rules, should be clearly identified in the Agreement or in the General Section of the Contract Specifications. It is not too important as to whether they are listed in the Agreement or the Contract Specifications, but it is important that they appear only once, since listing them twice will likely result in some inconsistencies; and then misunderstandings will arise.

The types of standards, which could be invoked, are, for example, IEEE 45, a recommended industry standard for marine electrical installations. Note, however, that unless otherwise mentioned in the contract documents, it is only a recommended standard. If it is to be binding on the Contractor, the Agreement should state that the identified standard should be treated as obligatory for this contract.

Other standards may address aspects of design, selection of materials, or quality of workmanship. Some other examples are: welding and brazing; electromagnetic interference; coatings; lighting and illumination; audio noise levels at various locations on the ship; vibration levels; air circulation in selected spaces; labeling of cables and piping; means of inspecting or testing components; and resilient mountings for machinery components, among others.

Often, shipyards will be familiar with particular standards in some of those example areas, in which case it probably would be reasonable to negotiate to accept that standard in place of a comparable one otherwise selected by the Purchaser.

The selection of which standards for detail design, material selection and workmanship should be made from this perspective: if an aspect of the Contractor's detail design, the quality of Contractor-selected materials or the workmanship of installation is going to be challenged by a Purchaser's inspector, there must be a documented standard which supports the challenge. There can be no dispute as to whether a standard applies if it is specifically named in the Agreement. As mentioned previously, however, including a non-applicable standard will only serve to confuse issues.

9.2.13 Contract Price

Under fixed-price contracts, the price for the Vessel has to be established, and the currency in which it is payable has to be stated as well. Working under a fixed-price contract, the Contractor has accepted considerable risk; but as discussed below, there are other alternatives. Some contracts will include additional protection for one party or the other in the event oflarge currency fluctuations; that is, there may be some mechanism to share the risks of currency fluctuations if the Contract Price is payable in a currency not normally used by one of the parties. The payment of the Contract Price is separately covered by the Agreement's section on progress payments, as discussed below.

If the form of the contract is other than fixed-price, such as cost-plus-fixed-fee, the exact mechanisms or procedures to determine the total of all payments must be described with specificity to avoid later disputes. Whether or not the Purchaser has the right to audit the Contractor's books to confirm such final pricing should be stated as well. The use of a form of contract other than fixed-price essentially alters the assignment of risks to suit the needs and acceptances of the parties. When the ship incorporates experimental or new technology about which the Purchaser has knowledge superior to that of the Contractor, it may be reasonable for the Contractor to avoid specific risks associated with implementing that technology; but in such cases, the Purchaser may also wish to exercise greater oversight in the implementation of that technology.

It is not uncommon for the Contract Price to be subject to automatic adjustment, without formal change orders. There is no risk associated with this provided the mechanism for the automatic adjustment is clearly stated. For example, if the quantity of a special material is not known with precision at the time of contracting, because the detail drawings have not been completed, the Contract Price may be automatically adjusted upon a material take-off after completion of the detail design.

The Contract Price includes allowance for the acquisition and installation into the Vessel of [W] thousand pounds of [material name], and shall be adjusted at the rate of [X] dollars and [Y] cents per pound in excess of that estimated weight, or eighty-percent of that rate of adjustment per pound if less than that estimated weight, upon completion by Contractor of detailed, as-installed, material take-off, subject to approval by Purchaser, which adjustment includes both material and labor costs.

The provision of spare parts may also lead to automatic adjustment of the Contract Price, if the quantity of spare parts which Purchaser wants is not known at the time of contract execution. Often, a Contractor will provide a list of recommended spares, and Purchaser will then determine which ones and how many are to be acquired. Because the Contractor did not know that quantity in advance, the price of the spare parts is added to the Contract Price, but the cost of acquisition and loading them aboard the ship are already included in the basic Contract Price.

Some Purchasers may wish to have the Contract Price stated in several components, but for new ship construction that is best addressed in the progress payments section of the Agreement, as discussed later in this section. For ship conversion or repair, line item pricing is often used, so that if the entire item is canceled, the adjustment of the Contract Price is known if cancellations are limited.

If the number of vessels is fixed but more than one, the Contract Price for each additional vessel must also be defined in this section. When the construction of a series of vessels being purchased under a single contract will extend for several years, the parties may agree to an escalation clause. Typically, after agreeing to the portion of the total price which is labor-based, material-based and subcontract-based, the cost of labor can escalate over time in accordance with an appropriate index, and the cost of materials and subcontracts can similarly escalate in accordance with perhaps a separate index. Usually the indices on which the escalation clauses are based are government-determined and widely published.

Of course, the Contract Price will also be subject to adjustment as the result of Change Orders, as discussed later in this subchapter.

9.2.14 Unit Prices

In anticipation of possible growth of the Contract Work Scope, negotiated through Change Orders, the Purchaser will have to utilize additional materials, subcontractor efforts, engineering and production labor. Further, extensions of the project schedule may necessitate the provision by the Contractor of additional days of shipyard services. If there will be significant shipowner-furnished equipment, the necessity of such additional items is more likely.

The cost impact of a Change Order may require negotiation of at least nine elements:

1. material costs,
2. subcontractor costs,
3. additional engineering hours,
4. production labor hours,
5. mark-up of material costs,
6. mark-up of subcontractor costs,
7. hourly rate for engineering,
8. hourly rate for production labor at straight time and overtime, and
9. daily cost of shipyard services. (Indirect effects of Change Orders, expressed as additional labor hours or other cost allowances may also have to be negotiated.)

The first four items will depend on the details of the Change Order itself. However, items 5-9 should be uniform for all agreed-upon Change Orders. Since those five items will have to be either competitively bid or negotiated, it is best to include their specific values in the Agreement. This avoids the necessity of negotiating them repeatedly or of negotiating them when other variables have to be negotiated as well.

In ship conversion and repair contracts, there may be a greater array of unit prices, such as for steel work, for piping, for blasting and coating, due to the increased likelihood that such changes will arise in those types of contracts.

9.2.15 Delivery of the Vessel(s) to Purchaser

The place and condition of delivery of the completed ship should be identified in the Agreement. Usually, the place of delivery is alongside the shipyard's dock; but sometimes for tax or financial reasons, the place of delivery may be at another location. If the vessel is not designed for open ocean service, it may require some temporary, contractor-installed modifications to sail to the place of delivery. Also, some government agencies, in seeking competitive bids from geographically diverse shipyards, will require delivery from the successful bidder, wherever located, to be at the agency's service dock.

The condition of delivery is usually that of a *warm* ship; that is, one that is not *cold* with none of the auxiliaries running and no heat or other services already in operation on the ship. For smaller vessels, such as tugs or other service craft, this differentiation is minor; but for larger ships, especially if steam powered, it may be more significant.

9.2.16 Project Schedule

The purpose of a shipbuilding project schedule is to give the shipyard a project monitoring and control mechanism. If properly developed and maintained (updated), it will enable the shipyard to see where it needs to redeploy its resources in order to keep the time-critical activities on schedule, and not inadvertently give priority of resources to non-critical activities.

The Agreement usually requires that the Contractor develop a detailed project schedule within a certain period of time after contract award, and that the Contractor provide copies of it to the Purchaser. Thereafter, the Contractor is usually obligated to update the schedule both periodically and if there are significant impacts due to Change Orders, and to timely provide copies of the updated schedules to the Purchaser. This requirement in the Agreement is sometimes supplemented by some technical details in the Contract Specifications. The maintenance of a project schedule can become quite important if the Purchaser is going to allege Contractor default as evidenced by comparing the actual status to a planned schedule.

Whether or not this clause is within the Agreement, the Contractor always has a duty to complete the ship by the Delivery Date stated in the Agreement. There are several reasons, however, to include this requirement within the Agreement.

First, by putting into the Agreement some minimum scheduling and updating requirements, the Purchaser is assured that the Contractor has allocated within its budget the resources for those actions.

Second, this assures the Purchaser that it will be entitled to see copies of the schedule and all updates.

Third, this enables the Purchaser to identify the Contractor's interpretation of latest requested dates for the arrival of shipowner-furnished equipment or materials or for other shipowner-responsible actions. The dates in the Contractor's schedule for shipowner-responsible actions may not be contractually binding if they have not been separately agreed upon at a prior time. However, the Purchaser should not ignore those dates when advised by receipt of a copy of the schedule, but rather should confer with the Contractor to establish dates that can be agreed upon, after which the Contractor may have to further revise its schedule.

Fourth, this allows the Purchaser to plan any necessary variations in the staffing of its inspection staff and, ultimately, the ship's crew.

Some agreements call for a *Key Event Schedule.* Key events could be the start of engineering, start of fabrication, start of hull erection, launching, sea trials and delivery

Some agreements authored by government agencies provide detailed requirements for the content and form of the project schedule, while some commercial shipowners are intentionally vague about the schedule's content and form. The choice of Gantt charts or the use of a critical path network (CPN) is one of the possible elements of this section. However, it may not be productive to require a shipyard to develop a CPN for a simple project, especially if the shipyard is not used to developing and using a CPN. Whether a Gantt chart or CPN is used, there should be four separate groups of activities indicated on the schedule: engineering, purchasing, production and testing. Any blending of those separate types of activities leads to risks of loss of project control.

9.2.17 Liquidated and Actual Damages (Delivery)

The purpose of this section of the Agreement is to set forth an acknowledgment by the Contractor that if the ship is delivered later than either the original Delivery Date or any agreed upon contract extensions, the Purchaser will incur financial damages; and the parties agree in advance that the damages are approximated by a certain sum per day of delay, payable by the Contractor. For legal reasons, this is not necessarily a penalty clause, although it may give the Contractor similar incentive to achieve timely delivery. If, however, it is phrased as a penalty clause for late delivery, then there should be a bonus clause for early delivery. If it is phrased as a liquidated damages clause, a bonus clause is unnecessary. Some contracts may include a clear statement that the Contractor is not entitled to any bonus for early delivery.

Another way of looking at this same clause is that it protects the shipyard in two ways. First, the shipyard knows in advance that its liabilities for delay in delivery are limited to the liquidated damages; and that the Purchaser cannot suddenly claim significantly-greater damages if the delivery is late, provided it is within the *cap* on liquidated damages, as discussed below. Second, the shipyard can view the daily amount of liquidated damages as the cost of *buying* a day of contract extension when it is not otherwise entitled to a contract extension. In some instances, that daily cost is less than the cost of accelerating the work to complete the ship on time.

Some shipbuilding contracts include several levels of liquidated damages. One form is to have a lower daily rate if the delay is identified to the Purchaser several months in advance, so the Purchaser will not incur costs of prematurely preparing the ship and its crew, or committing the ship for a charter or voyages. In that instance, the higher daily rate would apply if the delay is not identified until the last several months of the contract period.

Another form of multi -level liquidated damages is to use progressively higher daily rates for each successive groups of days. For example, each of the first ten days of delay may be at a specified rate; each of the second ten days of delay may be at, say, 125% ofthat rate; with similar progressions for several other groups of days, until the maximum number of days for which liquidated damages accrue is reached. This is illustrated for other percentages in Figure 9.2.

The liquidated damages may accrue for a stated maximum number of days, thus placing a *cap* on the liquidated damages. The existence of a cap on liquidated damages does not, by itself, limit the damages that a Purchaser may claim from the Contractor if the delay extends beyond the number of days used to achieve the cap.

Unless further provisions are stated, the cap means that the Contractor is exposed to additional, *provable* damages that the Purchaser incurs after the cap is reached. The contracting parties may wish to negotiate on this matter, possibly eliminating such *consequential* damages for the Purchaser if the Contractor is similarly prohibited from seeking consequential damages due to the actions of the Purchaser.

Occasionally, shipbuilding contracts will allow the Purchaser to not take delivery of the ship if the delivery date is unilaterally extended by the Contractor, without Purchaser's agreement, beyond a stated number of days; in which .case the Contractor refunds to Purchaser all progress paym~mts.

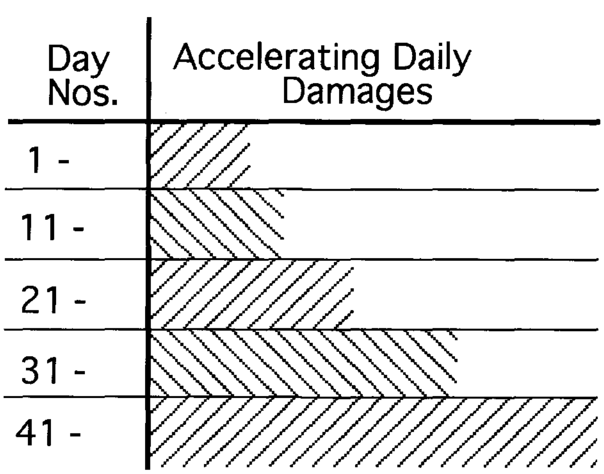

Figure 9.2 Daily Liquidated Damages (adjust days and $$$ as appropriate)

9.2.18 Liquidated Damages (Performance. Design)

The Contract Specifications and Contract Plans may provide target quantities, amounts, or dimensions for various aspects of the ship. Many of them will undoubtedly be achieved because of the design process. Some of them, however, may not be exactly achieved, such as maximum trial speed, minimum continuous operating speed, fuel consumption rate at design speed and draft, maximum deadweight, draft at maximum deadweight, or liquid capacity in certain tanks, among other possibilities. These possibilities are more likely to arise if the ship incorporates a new hull form, new technology or significantly greater powering than routinely installed in a similar ship, or if the shipyard has not previously constructed a similar vessel.

The essential point is that while the process of ship design and construction continues to advance, in some technical areas there are still no absolute assurances as to the net result or outcome that is built upon numerous engineering and design decisions. This matter is discussed more thoroughly in (4).

When the completed vessel does not achieve all of its intended design or performance parameters for which the Contractor was responsible, the Contractor and Purchaser have to negotiate a resolution to the discrepancies because the requirements of the contract strictly have not been fulfilled and the Purchaser is not getting all that was bargained for. Absent a harmonious negotiation, litigation is a distinct likelihood.

To avoid litigation, the Agreement can identify liquidated damages that would be payable by Contractor to Purchaser if the specific design or performance parameters are not achieved. For example, a certain sum of damages could be payable for each one-tenth knot less than the intended trial speed for up to a half knot deficiency. Then twice that amount per tenth of a knot for a speed deficiency between a half-knot and a full knot. Similar progressive liquidated damages could be stated for greater deficiency.

The Purchaser may insist, however, that if the trial speed deficiency exceeds a stated amount, the Purchaser has the right to not take delivery of the ship and to be repaid all progress payments. The Contractor can be offered a bonus for achieving a higher speed, but the bonus may be limited to a modest amount, regardless of the extra speed achieved, because the operator cannot use that speed or cannot afford the fuel to achieve it. A graphical illustration of this form of performance-based liquidated damages is shown in Figure 9.3. Similar progressive, or linear, liquidated damages and bonuses can be assigned to other key design or performance parameters, which are the net result or outcome of numerous engineering and design decisions.

9.2.19 Representatives of the Parties

The matter of identifying in the Agreement the person who constitutes the official representation of each party for contract purposes appears to be a fairly straightforward matter. However, during the completion of the design by the Contractor and during construction of the ship, numerous communications between the parties will be necessary (see Section 9.4 for identification of the types and management of those communications).

Each of the parties may wish to designate a single person to be the recipient oflegal notices and other higher-level communications; but may also wish to designate other persons to be the recipient or authority for technical matters.

For example, one person may have the decision-making authority pertaining to engineering and design developments; another may have authority to accept or reject the Contractor's material and equipment selections and its workmanship; and another may have authority to approve or negotiate progress payment invoices. There are additional functions, which can be assigned to other decision-making authorities for each party.

Perhaps the most important authority to designate is the one who can negotiate and accept amendments to the contract in the form of Change Orders. Each Change Order may modify the contractual statement of work, the Contract Price and the Delivery Date. Of comparable importance, the Agreement can also state that no persons other than the indicated representatives have any authority to modify the work scope, price or schedule, or accept design decisions or the workmanship of the Contractor.

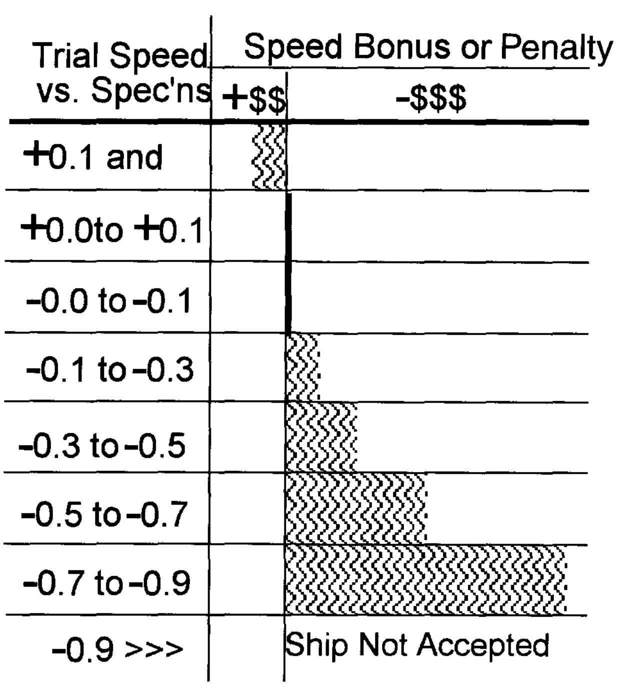

Figure 9.3 Trial Speed Bonus or Penalty

9.2.20 Examination of Plans

It is customary to arrange for the Contractor to give to the Purchaser copies of its detail plans and working drawings in advance of their need for production. This allows the Purchaser to examine the drawings and inform the Contractor of any comments or suggestions that may be appropriate, prior to the use of those drawings by the production department. As simple as that may sound, there are a significant number of issues that will have to be addressed, preferably within the Agreement, although some contracts address such matters in the general section of the Contract Specifications. The following discussion is a distillation of a thorough discussion of this subject in (2).

The purpose of the Purchaser's examination of the working drawings or detail plans should not be mis-stated; it is important to not give more responsibility to the Purchaser than is appropriate, nor to relieve the Contractor of its responsibilities through that drawing examination process. Some words used in contracts to describe this function of the Purchaser have been: audit; examine; review; or approve. The use of the word *approve* should be avoided because such *approval* of a working drawing could be interpreted to relieve the Contractor of responsibility for any errors in the drawing or any inconsistencies with the Contract Work Scope as already defined by the Contract Plans, Contract Specifications, and other components of the contract. If the Purchaser has approved the drawing, the Contractor may assume, among other possibilities, that the Purchaser has compared the drawing to classification rules, regulatory requirements, the Contract Specifications, or the Contract Plans, and that the Purchaser found that the drawing is in full compliance with all those requirements. The Contractor has already been assigned that responsibility in the Agreement; so the Purchaser should not relieve the Contractor of it through an *approval* of working drawings.

Agreements typically state a maximum number of days for the Purchaser to examine a working drawing before issuing any comments or suggestions to the Contractor pertaining to that drawing. The inclusion of that particular maximum duration in the Agreement ensures that the Contractor either will not start the related production work until taking into account the comments and suggestions as appropriate, or may start the production work but at the risk of having to revise it to accommodate the comments and suggestions. The Contractor also must allow sufficient time for regulatory and classification reviews of its drawings.

The Contractor usually is required, per the Agreement, to provide to the Purchaser in advance a drawing schedule, listing the drawings that will be developed and passed to the Purchaser for examination, as well the approximate dates by which those drawings will be completed. The scheduling of the completion of those drawings must be consistent with both the periods of time for examinations by the Purchaser, classification and regulatory bodies, as well as the timeliness requirements of the physical production department of the shipyard.

As discussed previously, the Contractor may have the authority to develop interpretations, design and details that are not already spelled out by any of the Contract Specifications, Contract Plans, applicable regulations, the nominated classification rules or identified standards. The Purchaser must avoid using the drawing examination process to second-guess the Contractor's decisions that have been exercised within its authority. Any attempt by the Purchaser, whether intentional or not, to micro-manage the design development process in areas for which the Contractor has that sole authority likely will result in extra costs, delays or disputes. Perhaps the Contractor will accept an occasional preference by the Purchaser, but more extensive imposition by the Purchaser will be burden that the Contractor need not accept. The drawing review process is not intended to be a mechanism for the Purchaser to direct the remaining development of the detail design.

This brings out a significant lesson that Purchasers have learned. The authority for design details that are not spelled out in the contract documents is typically given to the Contractor. When multiple *solutions* to a detail design requirement are available, there is no basis to expect that the Contractor will choose a solution that is exactly the same as desired or anticipated by the Purchaser. Accordingly, if a particular aspect of the vessel's detail design is important to the Purchaser, it should be completely addressed in the Contract Specifications and/or Contract Plans. It is not realistic to expect the Contractor's engineers and designers to be able to read the minds of the Purchaser's operating staff as to what those details are to be if they are not defined in the contract documents. Clearly, the process of examining or reviewing the Contractor's detail plans is not the mechanism the Purchaser should use to impose on the Contractor details that are not already defined in the contract documents.

During development of the detail design by the Contractor, the Contractor may wish to implement work which appears to achieve the *intent* of the contract design but which, in fact, strictly requires a change to the Contract Specifications or Contract Plans. Agreements usually state that a Change Order or waiver affecting the Contract Specifications or Contract Plans cannot be authorized by Purchaser's acceptance of a detail plan or working drawing, which incorporates such a change. This ensures that a change in the Contract Specifications or Contract Plans is not effected through the drawing review process, but only through the formal Change Order procedure.

9.2.21 Inspection of Workmanship and Materials

When the Contractor is selecting major items of equipment to satisfy the Contract Specifications, the Purchaser may wish to include in the Agreement the creation of a review process that occurs before the purchase is executed by the Contractor. In that case, the Purchaser would have an opportunity to examine in advance the technical aspects of the Contractor's purchase order, but not the pricing. The Purchaser should have to return any appropriate comments within a specified time so the Contractor's purchasing of the equipment will not be delayed.

One issue that often arises is the Contractor's selection of equipment which is identified in the Contract Specifications with the notation that the Contractor can select that particular item of equipment or its equivalent, or its equal. That selection is subject to review by the Purchaser in the same general manner as other equipment acquisition, which is subject to advance review by the Purchaser. However, there are several often-disputed aspects of the use of the *or equal* wording, which are discussed in greater detail in Section 9.3, Formation of Specifications, and in particular Subsection 9.3.10 on *Review of the Contractor's Equipment Selections.*

The right of the Purchaser to inspect work in progress, not just completed work, should be clearly stated in the Agreement. In further support of that concept, either the Agreement or the General Section of the Specifications can establish a mechanism for inspection, or quality, deficiency reports being issued by Purchaser to Contractor. The Agreement or Specification may require that once such a report is issued by the Purchaser, the Contractor must respond within a defined period of time as to how and when the Contractor will correct that deficiency. Related to this is the matter of Special Retainages, discussed in a later part of this section.

An important aspect of the Purchaser's inspection and possible rejection using an inspection deficiency report is establishing, in the contract documents, the basis for such possible rejection. This is discussed in greater detail in Section 9.3, Formation of Specifications, and in particular in Subsection 9.3.12, on *Inspection of Contractor's Workmanship.* The necessity of understanding all the possible problems associated with equipment selection and review and with inspection of the Contractor's workmanship presents another example of why technical personnel, not lawyers, should be the primary developers of this aspect of contract documents.

9.2.22 Changes in Specifications, Plans and Schedule

A Change Order is a formal amendment to the contract, which may incorporate changes in any of the Contract Work Scope, the Contract Price, the Delivery Date, the Terms and Conditions, or procedures set forth in the any of the contract documents. The area of greatest concern is that of changes to the Contract Work Scope, along with the associated cost and/or schedule impact.

When dealing with a government contract, it is more difficult to amend or change anything but the work scope, price and schedule, since many of the other facets of the contractually defined relationship are controlled by procurement regulations with which the government agency must comply in its contracting procedures.

This section of the Agreement is intended to define the procedures and mechanisms by which the parties can implement a change to any of the Contract Specifications, Contract Plans and/or Delivery Date. The three parts of the process are the request by the Purchaser, the proposal by the Contractor, and the bilateral Change Order, which either accepts the proposal or results from negotiations over that proposal.

Sometimes, but rarely, work scope changes come about due to requests by the Contractor, usually on the basis of being able to reduce costs if the shipyard is allowed to alter some aspect of the Contract Specifications and/or Contract Plans.

Primarily, work scope changes come about because the Purchaser has requested them. That request is usually based on the Purchaser, after the contract was executed, either changing its mind about some features on the vessel or having contracted before finalizing decisions about what it wanted. Some changes come about due to errors or inconsistencies in the Contract Specifications and/or Contract Plans. A separate textbook could be written about Change Orders; but the intention of this section is to describe only what aspects need to be addressed by the Contract Agreement.

It should be noted, too, that some Change Orders have no impact on work scope, but may require additional shipyard engineering, which is accomplished through a Change Order. For example, assume the Contract Plans show that a pair of generators is to be transversely mounted, but before the work begins the Purchaser requests they be longitudinally mounted. There may have to be additional engineering to alter the design of the foundations, supporting structures and connections; but the actual production costs essentially will be the same for the transversely mounted generators as for longitudinally mounted. Thus, if accomplished in a timely manner, an engineering Change Order would be appropriate with no production cost or schedule impact.

The Agreement establishes the mechanisms needed to formally achieve the Change Orders. First it has to address the matter of the request by the Purchaser for a change proposal from the Contractor. The Agreement must consider whether or not the Contractor has a duty to make a change proposal in response to a change request from the Purchaser, or if it can decline to make a change proposal. The Agreement must then indicate the normal period of time allowed for the Contractor to prepare the change proposal after receipt of the change request.

The period of time during which the Purchaser has to accept, cancel or negotiate the proposal after the change proposal is given to the Purchaser should be defined by the Agreement. If this is not a defined period of time, a risk develops that the Purchaser may accept the proposal much later than the Contractor anticipated when developing the price and schedule impact of the proposed change.

The Agreement should also provide that the Contractor can also make an unsolicited change proposal. Thereafter, the same procedures and mechanisms would be utilized to convert that change proposal into a Change Order.

9.2.23 Adjustment of Contract Price and Schedule for Change Orders

Agreements almost always require that the Contractor not proceed with the changed work until there is a bilaterally signed Change Order authorizing the change to the work scope. Thus, both parties will have had to consent, in writing, to the revised Work Scope, the impact, if any, on Contract Price, and the impact, if any, on Delivery Date. This section of the Agreement defines the process of achieving mutually agreed Change Orders. This sounds simple in theory, but is often difficult to implement. This section of the Agreement may also define that if the Contractor proceeds without such agreement, it is at the Contractor's risk.

There may be circumstances in which it appears to make good sense from a ship production perspective to begin implementing the change to the work scope prior to formal authorization of a mutually agreed upon Change Order. Proceeding in good faith with the change work, assuming the parties will eventually agree upon price and schedule impact, may create significant risk for either or both parties.

Some government contracts define the government's right, as Purchaser, to *direct* the Contractor to proceed with change work even when there is no agreement as to price and schedule impacts. The idea behind this is to ensure that the government will not be abused by a Contractor that may be perceived as trying to take advantage of the necessity of the change work. The intent, as may be defined by the Agreement, is that at some later time the parties will negotiate the price and schedule impacts; and if that negotiation is not successful, the Contractor can resort to other mechanisms to seek compensation for the work. Other mechanisms may be a Request for Equitable Adjustment or the use of the Disputes Clause within the Terms and Conditions. In some government contracts, if the parties cannot agree as to price and schedule impact, the government agency will unilaterally assign a price and schedule impact in order to have a basis for making progress payments for that work; but the unilaterally determined price and schedule impacts are inevitably less than those sought by the Contractor.

Some commercial contracts, especially in time-sensitive projects, include a similar right of the Purchaser's representative to *direct* the Contractor to achieve some previously undefined work before agreeing on price and schedule impact.

If a Purchaser, whether it be a government agency or commercial entity, *directs* a Contractor to proceed without prior agreement, even if the contract gives the Purchaser the right to direct the Contractor to undertake the change work, the risks associated with costs and schedule impact have to be considered. If the Agreement does not otherwise clarify which party is assuming which risks when there is a directed change, most likely the risk is being assumed by the party doing the directing, namely, the Purchaser. In view of that, the inclusion in an Agreement of the Purchaser having the right to direct changes should be carefully considered, and probably rejected, from the outset.

Changes, which come about due to regulatory, or classification requirements that must be achieved but which became enacted after the contract was first executed are considered a basis for a price and/or schedule adjustment. This section of the Agreement defines the conditions under which such adjustments may come about. In actual practice, the *interpretation* of such regulatory or classification requirements may change, causing the Contractor to incur extra costs, but the written requirements may not have been altered, in which case the Agreement usually states or implies that the Contractor is not entitled to an adjustment of price or schedule.

9.2.24 Extension of Time

This section of the Agreement addresses extensions to the Contract Delivery Date due to events beyond the control of the Contractor. These are sometimes known *asforce majeure* events, such as unusually severe weather, acts of the government, riot, strikes and labor disputes, among other possibilities. Some Agreements do not allow supplier failur~s or subcontractor defaults to be the basis of such excused delays, while others may allow such a basis for excused delays if the Contractor can demonstrate a direct impact on vessel completion schedule. This section of the Agreement also identifies the communications, which must be accomplished by the Contractor if *aforce majeure* delay is appropriate.

Some Agreements also address possible schedule impacts resulting from interpretations to the applicable regulatory and classification requirements. This is likely to be a focal point for disputes, because these problems may not arise from changes or alterations in the applicable regulatory or classification requirements. The problem may be in the third-party inspector's interpretation of those requirements. It is recommended that impacts arising from *interpretations,* but not from changed regulatory and classification requirements should not be a basis for extensions of time, since the Purchaser has not defined any specific interpretation in advance. In such instances, any interpretation by the third party, whether expected by the Contractor or not, is still consistent with the Contract Specifications, the Contract Plans and the referenced documents.

9.2.25 Final As-Built Drawings and Calculations

The as-built, or as-fitted, drawings and the final calculations and test data form an engineering database for the ship. Most Purchasers' require, through this section of the Agreement, that the Contractor is to provide such information as to form that engineering database.

These *deliverables* from Contractor to Purchaser have to be defined to ensure that the Contractor allows for their development in the project's budget and schedule. These may be defined as a combination of:

- various certificates to be issued by regulatory or classification organizations,
- standard calculations in formats defined by professional societies such as SNAME, and
- documentation that is unique in format or content to the particular contract or ship. The Agreement should also define whether each element of the documentation is to be transmitted only in hard copy (on paper) or if it also is to be transmitted electronically in computer-readable format. The Agreement may refer to a particular section of the Contract Specifications for the detailed format of those calculations and drawings.

The timeliness of delivery of those documents from Contractor to Purchaser should be defined within the Agreement; otherwise the Contractor has little motivation to accomplish them promptly if its engineering resources are temporarily needed for other projects. Part of that motivation may be generated through the progress payments section, as discussed below.

Some Agreements provide a schedule for delivery of the documentation in draft form to the Purchaser, and then delivery in final form after the Contractor's correction of the documentation in accordance with comments from the Purchaser.

It is not uncommon for disagreements to develop over the quality and/or accuracy of the *as-built* drawings. In order for those drawing to be accurate, personnel from the shipyard's drafting department must go on the completed ship to ascertain how the production department had to vary from the production plans in order to remedy interferences between structure and the various distributive systems, if composite drawings were not used. Typically, not wishing to incur those extra costs, shipyards will provide as-built drawings that the shipyard deems as adequate and of sufficient accuracy. If the Purchaser expects to receive accurate as-built drawings, appropriate controls over the process have to be included in the contract documents, including use of the progress payments clause.

9.2.26 Operating and Technical Manuals

The Contractor must also know the extent of operating and technical manuals that are to be provided with the ship. Some Purchaser's are content to accept the manuals that are provided by the equipment manufacturers only. Other Purchaser's, however, require system manuals, that is, manuals for the concurrent and inter-dependent operation of groups of components that form a system. Whatever the preference of the Purchaser, it must be defined in either the Agreement or, by reference, in an appropriate section of the Contract Specifications.

Absent such a requirement in the contract, the Contractor may perceive that it is not required to provide such technical documentation. If system manuals are required, they usually have to be developed by the Contractor or a specialist subcontractor, either of which may represent a significant cost to the Contractor.

Government contracts, especially for Navy and Coast Guard vessels, may require even greater *logistic support* technical documentation for which the cost of development may be a measurable percentage of the cost of the physical vessel. If these requirements are not defined within the Agreement or, by reference, within the Contract Specifications, it may become impracticable for the Purchaser to obtain them at a later date.

9.2.27 Tests and Trials

There are a significant number of tests and trials to which the vessel must be subjected in order to prove the workmanship and the operational capability of each component, and then each system, and then finally the entirety of the vessel. Many of these tests and trials are needed to obtain regulatory and classification approvals, but others are needed to give the Purchaser assurance as to the satisfactory completion of the work by the Contractor.

Each test and trial has cost and possibly schedule impacts. In order to include each of them in the Contractor's price and schedule, they have to be defined in the Agreement or, by reference, in the Contract Specifications. If special instrumentation or equipment is needed to accomplish the tests, it should be stated that Contractor is to provide those items, such as water bags or test weights for crane load tests and load banks for generator electrical load tests.

For some of the more complex trials, a definitive, draft trial agenda should be developed by the Contractor in advance, provided to the Purchaser for review and comments, and then finalized prior to those trials. The Agreement should establish the schedule and mechanisms for such developments. Several organizations, induding SNAME and ASTM as well as the Navy and Coast Guard, have standard test and trial agendas which may be the basis of the specific agendas developed for the new ship's trials.

The details of any tests and trials, as well as the standards to be used for test and trial agendas, should be in the Contract Specifications, but the necessity of them, especially those in excess of regulatory and classification requirements should be identified in the Agreement.

9.2.28 Warranty Deficiencies and Remedies

The warranty clause of the Agreement must address several specific issues, but the order in which the issues are addressed is not significant. It should be understood, however, that a warranty claim can apply only to an item which was working or completed at the time of Vessel Delivery, and subsequently broke or ceased to work sometime during the Warranty Period. An item which was not working or not completed at the time of Vessel Delivery may be corrected or completed during the Warranty Period, but it is financially treated in a different manner, as described below in the section on Special Retainages.

The duration of the warranty period should be defined. Related to that, the warranty clause should address how, if at all, the warranty period pertaining to some equipment, or perhaps the entire ship, is extended if that item or the entire ship is out of service due to a warranty defect.

The warranty clause must also define what is subject to the warranty: the Contractor's workmanship, the materials and equipment supplied by the Contractor, or both. Further, the warranty clause must define which entity is giving the warranty on each particular aspect of the ship. The clause may allow the Contractor to *pass through* any manufacturing warranties from vendors, such as pump manufacturers or coating suppliers, and provide that the Contractor does not otherwise warrant that item; however, the Contractor always warrants the workmanship of installing or applying those items. This may present some risk to the Purchaser if the manufacturer's warranty expires before the balance of the contractual warranty is to expire.

If an item of equipment is subject to the manufacturer's warranty, the Purchaser may find, subsequent to a breakage, that the manufacturer identifies the cause as one of improper installation. That is, for the Contractor to remedy, and the Contractor identifies it as a manufacturing defect, that is, for the manufacturer to remedy. This will create for the Purchaser a potentially unsatisfactory situation, which is best addressed by a contract retainage, as, discussed in Sub-section 9.2.30.

The matter of which party is to expend resources to correct a warranty item must also be defined. This can be complex since it must allow for:

- emergency repairs,
- possible remote location of the ship relative to the shipyard,
- timing of notification by the Purchaser to the Contractor of the existence of a warranty defect, and
- location at which it is possible to effect the warranty correction.

Subsection 9.2.30, Contract Retainages, addresses possible use of those retained funds to effect warranty repairs.

9.2.29 Progress Payments

A shipyard needs progress payments to cover the significant cash-flow requirements that are incurred by the shipyard during ship construction project. The cash flow relates to the regular payroll for all those working on the vessel's construction, the subcontractors, the vendors and suppliers, as well as for a portion of the overhead costs for the facility and organization. The shipyard's need for progress payments is not eliminated if the Purchaser decides to finance the construction by a mechanism which is separate from the final vessel mortgage financing. Either the Purchaser or the institution providing the construction financing will allow the Contractor to draw down against the arranged funds on a progress basis, which is pre-established in the Agreement.

It is in the best interest of the Purchaser to ensure that progress payments are made only for work already c~mpleted or materials and equipment already receive,d by the Contractor. **In** some instances, all progress payments have been linked to purely physical construction, but that is not recommended due to the risks it creates. The engineering, the component tests, the system tests, the dock trials, the sea trials, and the certificates and documentation to be provided with the ship all require expenditures by the Contractor. If progress payments are made on the basis of physical progress only, the Contractor has reduced incentive to fully and timely complete all of those tasks, which are not direct production work. Thus, an appropriate part of progress payments can be linked to those aspects of the Work Scope which are not physical production of the ship.

Consistent with Mr. Blakeley's words cited in the introduction to this chapter, there have been major contractual disasters brought about due to premature physical construction of ships; in the extreme, some resulted in scrapping of the ship after construction but before ever being put into service. The construction was premature due to inconclusive or incomplete models tests, research, engineering calculations or other activities affecting design development.

Progress payments can be used as a mechanism to discourage premature physical construction which might otherwise be undertaken prior to completion of activities, which are best, completed prior to the start of physical construction. For example, the Agreement can state that no progress payments associated with physical construction will be made until the delivery to the Purchaser of a satisfactory, detailed-but-preliminary trim, weight and stability booklet. On some vessels, damage stability may be more relevant. Similarly, progress payments against any electrical production work can be subject to completion of satisfactory electrical load and fault-current analyses. Other linkages between non-production work and progress payments may be appropriate, depending on the specifics of the project.

Non-production work items that do not have to precede production work, such as completion of as-built drawings, tests and trials, among other functions, can have their own progress payments associated with them. Simply, if the Contractor has received all the progress payments prior to delivery of the as-built drawings, for example, the Contractor has reduced incentive to apply its resources to proper updating and completion of those drawings once the ship has departed the shipyard.

The amount of the progress payments is based on contractually defined mechanisms. Some contracts break-down the total work into small percentages for each structural module, major components, mechanical or electrical system, and for each major part of the distributive systems (supply piping, return or drain piping, HVAC, electrical distribution). The parties then periodically agree as to the percentage that each of those systems has been completed, and a progress payment against that percentage completion is paid. This methodology for quantifying progress payments may not be accurate near the start of the project, but typically becomes fairly accurate near the end of it, as long as the non-production activities are being paid separately by their own progress payments.

Other contracts use well-defined milestones as the basis for progress payments. Depending on the nature of the ship construction project, a total of thirty to one hundred separate milestones may be defined, each having a particular percentage of the total Contract Price associated with its completion. At the end of every month, each of those milestones, which are 100% completed within that month become eligible for the associated progress payment. The non-production activities have their own set of progress payment milestones associated with them, too. For example, a particular progress payment may be for the structural machinery space module; another may be for receipt of all the tonnage and classification certificates.

The developers of the Agreement must have a clear understanding of the ship construction process, both production and non-production work, in order to develop an appropriate set of progress payment criteria. This is another basis for technical personnel to be controlling contract formation. Sometimes is appears that the Contractor wishes to negotiate into the Agreement earlier payment than the Purchaser is willing to allow. Although the cash flow requirement for the shipyard may be essential to its financial ability to timely finish the project, there is more risk to the success of the project if payment for not yet completed work is allowed.

9.2.30 Contract Retainage

Many Agreements provide for the Purchaser to retain a defined percentage of each progress payment. Thus, at the time of vessel delivery to the Purchaser, assuming all the deliverables other than the ship have also been completed, the situation is this: the Purchaser receives the ship and 100% of the other deliverables, but the Contractor has received a lesser percentage of the total contract price.

The purpose of the contract retainage is to provide for the circumstance in which the Purchaser may have to pay for a warranty correction when the Contractor is not able to timely accomplish it or when the Contractor allows the Purchaser to effect that correction. Another purpose of the contract retainage may be to protect the Purchaser in the event of a lien or claim by a supplier, vendor, subcontractor or other party which has contributed to the construction of the ship but has not been fully paid by the Contractor. To minimize the likelihood of such liens or claims, the Terms and Conditions usually require that the Contractor certify that the Vessel is being delivered free and clear of all liens, claims and encumbrances, and certify that all suppliers, vendors, and subcontractors have been fully paid.

For commercial contracts, the amount of the retainage, as a percent of the Contract Price, is negotiated during contract formation. On new commercial construction, it is usually no higher than ten percent, often five percent. Some Purchasers do not require any contract retainage. The absence of any contract retainage creates a risk, however minor it may be, that the Purchaser will have to disburse money for warranty corrections that properly should have been expended by the Contractor, with no cost-effective recourse to recovering that outlay.

For government contracts, the amount of the retainage is established in the request for proposals, or solicitations. Some government agencies require more significant retainages, which, in practice, may only serve to cause bidders to seek higher prices in order to deal with the impact on cash flow that such large retainages may have. From a government agency's perspective, a larger contract retainage allows longer payout for the ship; but in fact it may only serve to increase the cost of the ship.

The Agreement defines when the Contractor will receive the balance of the Contract Price, provided the Purchaser has not spent part of it in a manner allowed by the Agreement. The Contract defines a *temporary* business and legal relationship. From the outset, it is intended that the relationship will terminate upon the end of the warranty or guaranty period. Thus, all contract retainage should be finally paid to the Contractor no later than the end of the warranty period.

Some contracts provide that half or some other portion of the contract retainage be paid prior to the end of the warranty period, and the balance paid at the end of the warranty period.

9.2.31 Special Retainages

It is not uncommon that some items on the ship are incomplete or not fully functional at the time the ship is otherwise ready for Vessel Delivery. **If** those items do not affect ship safety, the ability of the ship to achieve its mission or perform its service, and if the correction or completion does not require the presence of the ship at a full-service shipyard, the parties may agree that the delivery of the Vessel will not be delayed by those deficiencies.

However, this creates a situation that is inconsistent with the intent of the contract, which intent was stated above, namely, at the time of Vessel Delivery the Purchaser receives the ship and 100% of the other deliverables, but the Contractor will have received a lesser percentage of the total contract price per the contract retainage. In other words, the Contractor is implicitly seeking a waiver of the requirement to deliver the ship in a complete and fully functional condition. In that case, the Contractor should not receive all the funds that otherwise would have been paid at the time of Vessel Delivery.

The Purchaser may grant that implicitly requested waiver if the contract retainage is ample to cover all of:

- the correction of those deficiencies,
- all warranty corrections, and
- any possible liens or claims by subcontractors and vendors.

However, such granting of a waiver creates risks if the Contractor does not correct the outstanding deficiencies. Under other clauses, the Purchaser may not have the right to use the contract retainage to rectify items which clearly were not warranty items, because they didn't break *during* the warranty period.

It is recommended that the Agreement allow the Purchaser to create a special retainage for each such uncorrected pre-delivery deficiency in order to give the Contractor incentive to have that deficiency corrected during the first half of the warranty period. At the end of the first half of the warranty period, any such special retainages are paid to the Contractor if the corresponding deficiency has been corrected. If it is not corrected by that time, the Purchaser can use those funds to have it corrected during the second half of the warranty period. The reason for that time limit on the expenditure by the Purchaser is, again, that the temporary business and legal relationship is expected to conclude at that time.

9.2.32 Technical Project as Basis of Agreement

The previous sub-sections of this section on Formation of the Shipbuilding Agreement have discussed the purpose and concerns of a number of the clauses of a typical commercial shipbuilding agreement. Other clauses may also be appropriate if they are not already included in the Terms and Conditions of the contract documents. Government contract forms will vary considerably among the many possible government agencies (federal, state, local, educational institutions, quasi-governmental agencies, etc.), but will all contain the equivalent of the clauses discussed above, as well as possibly others that are required by the agency's procurement regulations.

When a set of contract documents is being developed, the Agreement and Terms and Conditions are usually built up from a previous set of similar documents. If, ho~ever, the nature of the vessel acquisition is going to be significantly different, then the use of the prior documents as a starting point has to be addressed more carefully. For example, if the prior acquisition was for a ship of the Contractor's standard design, and the new acquisition is for a unique design, there are many aspects of the Agreement that will have to be modified. If the contractor has never constructed a ship ofthe type being acquired, a more-rigorous set of checkpoints may have to be incorporated into the Agreement and the supporting Specifications.

Essentially, besides establishing a temporary business and legal relationship between the Contractor and Purchaser, the Agreement and the supporting documents should identify potential risks (technical, financial and schedule), assign responsibility for avoiding those risks, and address the consequences if those risks are not satisfactorily avoided. Thus, the nature of the technical project and the risks associated with its achievement are the most important factors in the creation of the contract documents. The entire set of contract documents must be integrated and consistent with each other, but primarily must be appropriate to the technical aspects of the project.

9.3 FORMATION OF CONTRACT SPECIFICATIONS AND PLANS

9.3.1 Introduction

The Contract Specifications and the Contract Plans are technical documents which are non-ambiguously identified in the Agreement by those titles. The purpose of those documents is to define the technical products or deliverables which the Contractor is to provide to the Purchaser. The Agreement, or perhaps, but not preferably, the General Section of the Specifications, identifies the regulatory requirements and classification rules that are to be satisfied by incorporation of certain design and construction features into the vessel. Those design and construction features arising from regulatory requirements and classification rules, however, essentially are generic, not unique to the vessel being acquired under a specific contract. Many of the design and construction features identified by the Contract Specifications and Contract Plans are unique to the vessel, making it different from other vessels. These documents may also define other features that are not necessarily unique for this vessel, but are not included in the regulatory requirements and classification rules.

Thus, the Contract Specifications and the Contract Plans, as components of the contract documents, define the heart of the project and possibly make it different from other ship construction projects to the appropriate extent. This section first addresses the intent and limitations of those documents, and then generally addresses the components within those documents as well as special concerns associated with several of those components. This subchapter, however, is not a substitute for a course of study either on specification preparation or on the development of plans.

9.3.2 Non-Included Features

The Contract Specifications and Contract Plans define the unique features of the vessel and other non-unique features that are not already addressed by the appropriate regulatory requirements and classification rules. It was pointed out in Subsection 9.1.15, under the topic of Decision- Making *Authority*, that numerous details which are not already defined in the Contract Specifications and Contract Plans, will have to be developed by the Contractor after the contract is executed. Except for unusual cases, when the parties executed the shipbuilding contract, the authority to make those additional decisions as to the form of the numerous details was passed from the Purchaser to the Contractor. The Purchaser's naval architects and marine engineers who are developing the Contract Specifications and Contract Plans must keep in mind that they will have yielded to the Contractor the right to make those decisions.

Thus, if the exact form of any lesser details is important to the Purchaser, the Contract Specifications and Contract Plans should describe them to an appropriate level of detail. If such details are not already incorporated into the Contract Specifications and Contract Plans, generally the Purchaser will have to accept the Contractor's *solution* to those details. The Purchaser's staff should bear in mind that it is most likely the Contractor will be seeking minimum-cost solutions to those technical details when working under a fixed-price contract.

The Purchaser's naval architects and marine engineers should not use the drawing review process as a mechanism to impose on the Contractor a more-expensive solution if the Contractor's solution is in all regards consistent with the contract documents. For example, if the form of mounting an item of equipment on a deck is important to the Purchaser for reduced noise transmission, that form of mounting cannot be announced after the Contractor has prepared drawings or even after the contract has been executed. Rather, because the form of mounting to minimize noise transmission likely will cost more than another form of mounting, the Contractor should have been given the opportunity to consider it before developing its bid price for the work.

9.3.3 Identifying the Required Type of Specification

In general, there are three types of specifications:

1. design or end product specifications,
2. performance specifications; and
3. procedural specifications.

Each of these three types of specifications leads to a different assignment of responsibilities between the Purchaser and the Contractor. A typical Contract Specification will include, for all the different aspects of the ship, more than one type of specification, and may even include all three types. The type of specification used for the hull form, for example, can be entirely different from the type of specification used for the ballast pumps.

A *design or end product specification* is a representation, by either drawings or verbal descriptions or both, of what that aspect of the ship should look like upon completion. The use of a Contract Plan for the hull lines serves to define the form of the hull from which the Contractor cannot vary. The hull form may be subject to variance if confirming model tests are to be conducted by the Contractor. Another example of a design or end-product specification may be for hull coatings. The Contract Specification may define the type, composition and color of the coatings, as well as perhaps the manufacturer, and then go on to define the thick nesses of each of the primer, undercoat and topcoat. That is, the final configuration of the coatings, layer-by-layer, has been defined by the Contract Specifications. An associated procedural specification, as discussed below, establishes the criteria for appropriate surface preparation and material application.

A *performance specification,* on the other hand, does not in any way describe what the object will look like, but instead will describe how it is to perform. A specification for the ballast pumps on a ship, for example, could state that the two ballast pumps shall each separately be capable of pumping into and out of the ship's ballast tanks a certain number of tons of ballast water per hour. Thus, the shape, material content, and weight, among other parameters, for each of those pumps will be selected by the Contractor provided that each can pump the required number of tons of ballast water per hour. Note, too, that a loosely written specification for two ballast pumps of equal capacity may even result in two different brand names; it is all at the discretion of the Contractor under a performance specification. The Purchaser can write a *tighter* specification to avoid that two-brand possibility. See Subsection 9.3.9, following, on Brand Names or Equal to supplement this discussion.

A *procedural specification* usually supplements one of the two other forms of specification by defining part of the procedure that is to be followed in achieving the other part of the specification, either in the design process or the construction stage. An example of a construction procedural specification pertains to coatings: the design specification for the coatings, as described above, may be supplemented by a procedural specification that requires the Contractor to apply the coatings in accordance with the practices recommended by the coating manufacturer pertaining to surface preparation, air temperature, steel temperature, relative humidity, direct sunlight, wind speed, etc.

An example of a design procedural specification may relate to power and signal cables. The design of the cable trays may be solely at the discretion of the Contractor, other than regulatory requirements and classification rules. That is, the cable trays are defined by a performance specification. However, that performance specification may be supplemented by an applicable design procedural specification which may state that when designing the cable trays, the Contractor shall also comply with the requirements of an identified electro-magnetic interference (EMI) standard to ensure that the EM emissions of power cables do not interfere with the signals within the control, alarm and monitoring cables.

The naval architects and marine engineers who develop the Contract Specifications and Contract Plans for the Purchaser can select whichever form of specification best suits the needs of the project for each item and each aspect of the ship. However, it is their responsibility to ensure that all of those specifications are compatible with one another. For example, if the EMI procedural specification requires two levels of cable tray to avoid the interference, the ship's basic design by the Purchaser's staff will have to provide ample space for those two levels; otherwise the requirements imposed on the Contractor may be impossible to achieve.

9.3.4 Standard Forms of Specifications

The technical Contract Specifications can be arranged in nearly any sequence; but there are standard sequences that have been used by industry in various countries. In the United States, for example, the U.S. Maritime Commission in the 1930s and 1940s, followed by the U.S. Maritime Administration in more recent years, developed and used a standard set and sequence of section headings, as indicated in Table 9.V. Each ofthose section headings includes multiple standard sub-headings (not shown herein due to size and number).

The value of using a standard group of headings and a standard sequence is that both shipowners and shipyards have become accustomed to using those standards. Of course, many of the section headings in Table 9.V may not be applicable to every project, and thus those section numbers should not be used. Other widely used standard specification headings can be used as well. A major benefit of starting with a standard is that is reduces the likelihood of inadvertently omitting some specification items. Additional sections for special shipboard features can be added by selecting section numbers that are not already used.

As to the actual content of the sections, distinct from the headings, it is noted that generic guideline, example or standard specifications also have been developed and published by many organizations worldwide. Sometimes those published specifications are quite helpful to persons developing specifications for a particular aspect of a ship for the first time. A review of such publications by specification writers will help assure that salient points will be addressed in the new specification, though it is not necessarily as suggested by the guidelines. When the ship type, or the system within the ship, is innovative or represents a new application of existing technology, the final specification may have only faint resemblance to the previously published specifications.

The U.S. Navy, for example, has used its *Gen Specs,* being general or standard specifications for defining particular aspects of the intended product in naval construction. With rapidly developing materials technology and innovative design concepts, however, those Gen Specs do not appear to be as relevant to each new class of vessel as they once had been. Since the mid-1990s, the U.S. Navy has been relying less on these Gen Specs and more on specifications developed for the particular vessel design, materials technology and application concepts being employed in the development of its newest ships. That Gen Spec should not be confused with the section of general specifications contained within most contracts.

The U.S. Maritime Administration has published *Guideline Specifications for Merchant Ship Construction.* The most recent edition (1995) is intended as a helpful generic package for ship operators and shipbuilders who will design specific commercial ships. That publication states, *"These specifications can be used as starting points for the preparation of construction specifications for any type of ship .... [They] are intended to provide guidance to the maritime industry for the preparation of specifications .... They cover all aspects of potential contract work, but may require modifications, as appropriate, to the ship design being contemplated."*

Recognizing that the value of such specifications has diminished due to numerous developments, the U.S. Maritime Administration no longer intends to update its published specifications.

Because published specifications, from any source, are only generic, guideline, example or standard, the contract specification has to be more supportive of the exact ship type

TABLE 9.V Possible Specifications Section Headings

1 General	53 Main Shafting,Bearings, Propeller	79 Ladders, Gratings, Floor Plates, forms & Walkways in Mach'y
2 Structural Hull	55 Distilling Plant	80 Engineer's and Electrician's shops, Stores And Repair
3 Houses And Interior	56 Fuel Oil	81 Hull Machinery
4 Sideports, Doors, Hatches,	57 Lubricating Oil	85 Instruments and Miscellaneous Boards-Mechanical
5 Hull Fittings	58 Sea Water	86 Spares-Engineering (Crating And Storage)
6 Deck Coverings	59 Fresh Water System	87 Electrical Systems, General
7 Insulation, Linings And Battens	60 Feed and Condensate	88 Generators
8 Kingposts, Booms, Masts, Davits	61 Steam Generating	89 Switchboards
9 Rigging and Lines	62 Air Intake, Exhaust and Forced Draft	90 Electrical
10 Ground Tackle	60 Feed and Condensate	91 Auxiliary Motors and Controls
11 Piping--Hull Systems	61 Steam Generating	92 Lighting
12 Air Conditioning, Heating and Ventilation	62 Air Intake, Exhaust and Forced Draft	93 Radio Equipment
13 Fire Detection And Extinguishing	63 Steam and Exhaust	94 Navigation Equipment
14 Painting and Cementing	64 Machinery Space	95 Interior Communications
15 Navigating Equipment	65 Air Conditioning & Refrigeration Equipment	96 Storage, Batteries
16 Life Saving Equipment	66 Ship's Service	98 Test Equipment, Electrical
17 Commissary Spaces	67 Cargo Refrigeration-Direct Expansion System	99 Centralized Engine Room and Bridge Control
18 Utility Spaces and Workshops	68 Liquid Cargo	100 Planning And Scheduling, Plans, Instruction Books,
19 Furniture and Furnishings	69 Cargo Hold Dehumidification	101 Tests And Trials
20 Plumbing Fixtures & Accessories	70 Pollution Abatement and Equipment	102 Deck, Engine and Stewards Equipment and Tools,
21 Hardware	71 Tank Level Indicators	103 Requirements For Structure-borne Noise
22 Stowage & Protective Covers	72 Compressed Air	
23 Miscellaneous Equipment Stowage	73 Pumps	
24 Name Plates, Notices andMarkings	74 General Requirements For Machinery Pressure Piping	
25 Joiner Work and Interior	75 Insulation-Lagging For Piping and Machinery	
26 Stabilization	76 Diesel Engines Driving Generators	
27 Container Stowage and Handling	78 Tanks-Miscellaneous	
50 Main And Auxiliary		
51 Main Diesel		
52 Reduction Gears and Clutches-Main		Appendix A: Owner Furnished Equipment

and the newest materials technology to achieve the intended result. Also, because published specifications try to be applicable to multiple ship types and multiple situations, it is likely that the contract specifications could be briefer than the published ones. Specification writers should be cautious, however, regarding the goal of achieving brevity in their work. It sometimes appears that due to the absence of information deleted for the sake of brevity, such shortened, and thus possibly ambiguous, specifications may lead to disputes.

9.3.5 Contract Deliverables

At the beginning of this section it was stated that the purpose of the Contract Specifications and Contract Plans is to define the technical products or deliverables which the Contractor is to provide to the Purchaser. Note the use of the plural of "technical products or deliverables." The Purchaser is paying the Contractor not only for the ship itself, but also for numerous other deliverables. Without many of those other deliverables, the ship by itself is not completely usable or maintainable by the shipowner. Some of those deliverables are defined by the applicable regulatory requirements and classification rules. The rest have to be defined by the Agreement, primarily the financial deliverables, or the Contract Specifications, primarily the technical deliverables.

The contract deliverables, other than the hardware of the ship and spare parts, will take many forms. Some ofthe deliverables will be engineering calculations, trim, weight and stability calculations, finite element analyses, fatigue strength calculations, electrical load and fault-current analyses, heat-load and heat-balance calculations, among others.

Some will be drawings, detail plans for review, classification-approved plans, as-built/as-fitted drawings, and others); some deliverables will be copies of shipyard correspondence with classification and regulatory bodies; some will be certificates from classification and regulatory bodies, and possibly from others. Some deliverables will be test and trial agendas and subsequent reports, and some will be warranty forms from vendors and others; and some deliverables may be shipyard scheduling information, hazardous waste disposal records, insurance information, among many other possibilities. This list is by no means complete.

The completion and delivery of each of those deliverabIes from Contractor to Purchaser represents a source of costs to the Contractor. If each of them is to be accomplished, the Contractor must know about them prior to bidding or pricing the work in order to have the budget available for each of them. Accordingly, the persons developing the Contract Specifications for the Purchaser must ensure that each such deliverable, hardware, drawings, calculations, correspondence, computerized files, etc. is identified as a required deliverable in the documents made available to bidding shipyards from the outset. All of the deliverables, besides the ship itself, have to be defined by the contract documents or they are beyond the work scope requirements of the Contractor.

9.3.6 Defining the Complete Scope of Work

In addition to the ship, the spares and all the other contract deliverables, the entire scope of work which the Contractor will have to undertake needs to be defined to the extent that there is sufficient information in the bid package or at the time of contract negotiations such that the Contractor can identify and estimate all sources of costs. In other words, if an shipowner's requirement for any information, materials or special tests will cause the Contractor to incur costs, such items must be separately identified in the contract documents as a Contractor responsibility.

Some examples of such items are:

- the payment of fees for classification and regulatory approvals, if needed,
- confirming model tests if they are to be accomplished after contract signing,
- maintenance of a detailed weights-and-centers spreadsheet for every item of equipment if appropriate,
- rental of testing equipment if it will be needed (test weights, electrical load banks, etc.), and
- any special testing requirements on shipowner-furnished equipment that the Contractor has to perform.

There are some aspects of technical specifications that cannot be glossed over without increasing the likelihood of some consequential disputes. A negative example, one to be avoided, is illustrated by the following wording taken from a recent specification. *"All work necessary to peiform the specified work shall be deemed to be part of the specified work whether specified or not."* This was an attempt by the specification writers to convey to the Contractor the responsibility to make everything complete and functional at no extra cost to the Purchaser. However, such wording is too broad to be usable for estimating and pricing, and thus likely could not be enforced in court.

The intent may have been to include, for example, the unspecified supply and installation of remote motor controllers for some of those electrical motors defined by the specifications. But inasmuch as the specification writer had information particular to the specified motor, that writer was in a better position to know if a remote motor controller would be needed. When estimating the work scope, the Contractor would not automatically know that a remote motor controller would be required, and thus the cost of it would not be included in the fixed contract price.

A Purchaser should not rely on requirements such as *first class marine practice* or *best marine practice* or other ill-defined phrases in order to ensure quality of material selection or quality of workmanship. Highly subjective requirements, phrased as those, are not conducive to quantitative estimating, and thus cannot be included in the price of the shipbuilding contract.

It should be remembered that, in soliciting bids or requesting pricing from a potential Contractor, the Purchaser is seeking quantities, quantities of production hours, material costs, subcontractor costs, facility and equipment costs, and schedule days. Accordingly, all aspects of the Contract Specifications and Contract Plans must be suitable for *translation* into such quantities. Broad concepts, such as the negative example given above, are not directly translatable into quantification prior to accomplishment of most of the remaining design development, and thus do not constitute well-defined specifications.

9.3.7 Shipyard Schedule and Updates

Many requests for proposals or similar solicitations by shipowners from bidding shipyards require that a preliminary schedule be supplied with the bid to ensure that the bidder has an understanding of the work scope comparable to that of the Purchaser's staff. It is common, but not necessary, for the contract documents to require that the Contractor provide the Purchaser with a detailed schedule within a stipulated period of time after contract execution. There are many reasons why the Purchaser's staff wishes to see that schedule, some of which have been discussed in Section 9.2 (see the subsection on Project Schedule) and some of which are discussed in Subsection 9.4 on Management of Contracts During Performance.

The Contract Specifications may present more detailed requirements for the project scheduling to supplement the general requirements of the Agreement. The more detailed requirements may address, for example, the use of separate activities for each of engineering, procurement, installation and testing for each item of equipment. The necessity of providing the Purchaser with updates may be supplemented by stating that such updates shall be made periodically, the period depends on the particular project, or more frequently if major changes have been agreed upon.

If both the Agreement and the Contract Specifications address the Contractor's responsibilities regarding project schedule, it is essential to ensure that they complement one another and do not conflict.

9.3.8 Engineering Design Responsibilities

In Section 9.1, Subsection 9.1.15 on *Decision-making Authority* pointed out that between the Contract Specifications and Contract Plans, on one hand, and the shipyard's detailed plans or working drawings, on the other, numerous developmental design decisions likely will have to be made. Some of them will be guided or controlled by the regulatory requirements, classification rules or identified standards, such as industry standards or Mil Specs, but many others are not so guided or controlled. In almost all shipbuilding contracts, when the parties executed the shipbuilding contract, the authority to make those decisions was passed from the Purchaser to the Contractor. The only residual decision-making authority that the Purchaser retains is indirect confirmation through review of the detail plans or working drawings.

From the shipyard's perspective, however, that decision-making authority is a mixed blessing. It is appreciated by shipyards because it gives shipyards the authority to seek least-cost solutions to ship production. In contrast, however, it puts them at a disadvantage when bidding the work because each shipyard does not know with certainty how much economy, compared to the Contractor's competitors, it will be able to build into the vessel though the use of such opportunities.

A shipyard is put at a further disadvantage when it has responsibility for significant design development because it must use or hire naval architecture and marine engineering design staff or subcontractors to accomplish that design development. This creates risks for the shipyard because the naval architects may be more likely to perfect the vessel's performance attributes or operational efficiency instead of making the ship more economically producible (see Chapter 14-Design/Production Integration).

The Purchaser's staff, when developing the Contract Specifications and Contract Plans, should bear in mind the shipyard's general wariness at having to incur such risks arising from undertaking significant design development. This does not mean that a Purchaser must allow the Contractor to avoid that responsibility, but it does mean that the Purchaser, through the Contract Specifications and Contract Plans, must ensure that it is perfectly clear that the Contractor will, in fact, have those responsibilities as appropriate to the project.

Accordingly, the Contract Specifications or the Agreement must clearly define the Contractor's responsibilities to perform all the engineering and design development tasks necessary to translate the requirements of the contract documents into material procurement, equipment procurement, detail plans, working drawings, and production plans, all of which are then used for ship production. If the Purchaser is not going to be providing any additional engineering or design support for the project, it might be best to clearly state, rather than merely imply, that no additional design information is being provided by the Purchaser.

When the Purchaser is assigning to the Contractor such responsibilities, the Purchaser's technical staff should be mindful of the fact that they will no longer have control over those decisions. If the Purchaser's technical staff is concerned that the Contractor may find means of making the ship construction too economical to suit the Purchaser, then *tighter* or more-detailed specifications should be developed for those particular aspects of the ship that are of greatest concern to the Purchaser. A Purchaser's technical staff should be cautious when responding to a Contractor's request for additional design information by means of *clarifications.* This may be symptomatic ofthe Contractor's reluctance to undertake the design effort that it is contractually obligated to accept. Further, it may lead to allegations by the Contractor that the design information, if provided by the Purchaser, implies a greater work scope than otherwise required, thus necessitating a Change Order.

9.3.9 Brand Names! Or Equal

One mechanism that is often used in Contract Specifications developed by the Purchaser is to identify a particular brand name and model number of an item of equipment, and then state that the Contractor must provide and install that particular item *or equal.* The intent, by the Purchaser, is to ensure that a certain quality is achieved. While this may be a worthwhile effort, it may not lead to the Purchaser's expected results for any of several reasons.

When an *or equal* mechanism is utilized in the specifications, the specifications usually reserve to the Purchaser the right to accept or reject the substitution proposed by the Contractor. The Purchaser can minimize the likelihood of a misunderstanding of what will or will not be acceptable by giving greater definition. In particular, the Contract Specifications could define what parameters are going to be considered when determining if a shipyard-offered substitution is truly *equal.* For example, the parameters that could be important for a motor/pump combination on a high-speed passenger ferry likely would be different than those being considered for a large tanker. Table 9.VI presents a partial list of parameters that might be considered in such situations; other parameters would be appropriate for other forms of equipment.

Another mechanism used in shipbuilding contracts to limit the choices for equipment that will be made by the Contractor is to negotiate or include a *maker's list* for various items. The maker's list identifies the brand name and model of equipment that is included in the base-line design.

Some maker's lists will include more than one possible brand name and model for several particular items of equipment. Whether or not the Contractor has the right to seek an equivalent to the items on the maker's list must be defined in the contract documents; without such clarification, the Contractor may interpret that it does have such rights and the Purchaser may interpret that it does not.

TABLE 9.VI Selected Parameters for Determing Equivalency of Combined Pump/Motor

Maximum Continuous Rate of Output
Maximum Peak Rate of Output
Pressure at Various Rates of Output
Materials of Construction
Weight
Audible Noise
Vibration Transmission
Mean Time between Failures
Metric or Non-metric Fittings
Electrical Feedback Characteristics
Controllability of Rate of Output
Power Requirements and Efficiency
Availability of Spare Parts
Availability of Tech Rep's
Proven Marine Experience
Manuals in the Selected Language
Ease of Maintenance
Commonality with Purchaser's Fleet

9.3.10 Review of the Contractor's Equipment Selections

In Subsection 9.2.20, the Purchaser's review of the' Contractor's detail plans and/or working drawings has belen discussed, In a similar manner, some Purchasers may seek to review the Contractor's selection of major items of equipment that are not already identified by brand name and model number, or are not covered by an *or equal* clause, or are not included in a maker's list. The purpose of the Purchaser's pre-purchasing review of the Contractor's purchase technical specifications that will accompany a purchase order is to ensure that the Contractor's interpretation of the Contract Specification's requirements pertaining to that item of equipment is compatible with the Purchaser's interpretation, If the Purchaser seeks to have this right of an advance review of the purchase technical specifications for selected items of equipment, the contract documents should create that right, remind the Contractor to provide the purchase technical specifications on a timely basis so as to not delay the schedule, and indicate the period of time that the Purchaser has to conduct such review,

As with the review ofthe Contractor's detail plans and/or working drawings, some Purchasers may try to use this review process to *persuade* the Contractor to adopt the Purchaser's interpretation when, in fact, alternate interpretations may also be valid, When the contract was executed, the Purchaser not only gave the Contractor the responsibility to select that item of equipment, but also gave the Contractor the right to select it to maximize the benefit to the Contractor. The burden of demonstrating that the Contractor-selected item is not compatible with the contract documents lies with the Purchaser. If the Purchaser can show that the Contractor-selected brand name and model does not satisfy the contractual requirements, the Contractor must revise its purchase order to achieve such compliance,

In some cases, the process of such review may lead the Purchaser to appreciate that, although the Contractor's selection is consistent with the contract documents, the Purchaser now sees that such a valid, alternate interpretation of the contract documents leads to a less-than-satisfactory equipment selection, The Purchaser may then seek to use this review process as a basis for requesting a Change Order to achieve a more-satisfactory equipment selection, However, this action by a Purchaser may result in higher costs, delays, impacts on drawings and engineering, and secondary impacts on other contract deliverables.

9.3.11 Resolution of Interferences

Composite drawings present isometric views of spaces or compartments within the ship, including scaled representations of all structure, equipment items and distributive systems. If prepared in advance of physical construction, composite drawings can identify physical interferences that would result from the use of unmodified Contract Specifications and Contract Plans. Today 3D product models can perform the same function. It is not a common practice for the shipowner's naval architects and design engineers to prepare composite drawings of the structures, items of equipment and distributive systems shown in and/or described by the Contract Specifications, Contract Plans or other contractually-defined standards. Thus it is possible, if not likely, that interferences between elements of the contract design will result from a strict interpretation of the contract documents.

In the event that the resolution of such interferences has an impact on the productivity of the shipyard's crafts, the Contractor may look to the Purchaser for compensation for that rework or temporarily-reduced productivity. To avoid that situation, either the Agreement or the Contract Specifications could advise the Contractor of the possibility of such interferences, require the Contractor to not undertake physical construction until the possibility has been examined and addressed, and further require that the resolution of such interferences are to be achieved by Contractor at no additional cost to Purchaser. In ship conversion or repair, the Contractor could be given access to the vessel for a pre-bid ship check to identify potential interferences if the Contractor is responsible for the correction of them at no additional cost.

9.3.12 Inspection of Contractor's Workmanship

The Agreement, as discussed in Section 9.2, usually includes a clause which establishes the right of the Purchaser's representatives to have access to the vessel and shops, including subcontractor sites, and to inspect work in progress. The use of inspection deficiency reports, or quality deficiency reports, has also been addressed in Subsection 9.2.21 in the section on Inspection of Workmanship and Materials. Inspection deficiency reports should only be issued if the Purchaser's representative can point to a part of the Contract Specifications or Contract Drawings with which compliance has not been achieved.

Many Contract Specifications state that the Contractor's workmanship shall be adjudged by the Purchaser's representative, and only that individual shall have the authority to make a determination of satisfactory workmanship. However, if there is no other identified standard against which the workmanship will be measured, the Contractor is effectively being asked to work to the unwritten standards in the mind of that Purchaser's representative. This is often an unsatisfactory mechanism, since the Contractor cannot know in advance what standard will thus be applied.

Accordingly, the Contract Specifications should include sufficient information to provide a non-ambiguous basis for determining if the Contractor's workmanship is adequate. Certainly the workmanship must satisfy the applicable regulatory requirements and classification rules. The workmanship must also satisfy any applicable standards that are identified in the contract documents, usually in the Contract Specifications or in the Agreement. These referenced standards may be marine industry standards, professional society standards, such as SNAME standards, well-distributed government standards, such as U.S. Navy Mil Specs, or even standards that are applicable but not necessarily unique to the marine industry. The Agreement or the General Section ofthe Specifications typically contains express language requiring the Contractor to correct, at no additional cost to the Purchaser, any workmanship or materials which fail to meet the standards.

The lack of an identified standard against which workmanship can be judged creates risks for both parties, which risks may result in disputes, an unsatisfactory product, rework and delay. Thus, the developers of the Contract Specifications should take the time and effort to include therein the standards against which the on-site Purchaser's inspectors will determine the acceptability of workmanship that is not already covered by applicable regulatory requirements and classification rules.

9.3.13 Identification of Item's Entire Work Scope

This is the heart of technical specification writing. It is a fairly complex matter, and not to be undertaken lightly or by unpracticed personnel. The history of risks and consequences that are associated with incomplete or misleading specifications is a sufficient basis for many books; these are the previously mentioned *contractual disasters.* As a foundation for discussing this subject, four points that have been already discussed are brought to the forefront.

First, at the beginning of this section, the three basic forms of specifications were discussed: design or end product; performance; and procedural.

Second, the desirability of avoiding too-broad specification language was also discussed. The negative example was given, *all work necessary to accomplish the specified work* .....

Third, the fact that the Contractor is given rights, not just responsibilities, to make decisions about details and materials after the contract is executed has been discussed several times in Sections 9. 2 and 9.3.

Fourth, the shipyard's decision-making authority gives it the right to implement least-cost solutions in design development and materials selection as long as it remains consistent with the Contract Specifications, Contract Plans, the defined regulation, the selected classification rules and the identified standards.

The identification of the entire work scope for each item requires that those four points be kept in mind when each element of the technical specifications is developed. For each element of the technical specifications, the specification writer must be able to express in words and in supporting sketches or drawings what is important, and therefore stated unambiguously, and what is also to be included but is not as important, allowing the Contractor to make detail decisions.

Each technical specification must reveal whether the performance is important to the shipowner, or if the form/design/configuration is more important. If the specification is a design or end product, generally the Purchaser is responsible for performance. A contract which includes a *design certification process* by the Contractor may serve to alter the assignment of certain risks. Precisely which risks and responsibilities are different from the usual form of contract will depend on the specific wording of the section of the Agreement which describes the design certification process. If certain procedures and/or standards are to be used or achieved in the development of details or the execution of the work, those procedures and standards must be clearly identified.

The writer of technical specifications must also understand what decisions the Contractor may be able to make with respect to each technical aspect while still being consistent with the contract documents, and determine whether a possible *least-cost* solution will be acceptable; if not, a more tightly defined solution is to be specified.

All of the elements of the workmanship and materials must be adequately defined to enable a shipyard to translate the technical specification into quantities, labor hours, material costs, and subcontractor costs, or the performance capabilities of the technical item must be translatable into such quantification after the Contractor's suitable pre-bid design effort.

There is no single style or form of technical specifications that is superior to other possible styles or form. Each organization developing Contract Specifications and Contract Plans should use the style and form with which it is most comfortable, provided that such style and form has not resulted in prior contractual disasters or near-disasters. Individual styles or forms should give way to corporate styles and forms, so that a Contractor is not confronted with different styles or forms in the same Contract Specification.

A specification-related risk that is too often encountered is that of *pride of authorship.* Even if a contractual disaster or near-disaster has previously resulted from the use of a particular wording of a specification, the writers of it may continue to believe that the troubles were not due to the specification, but rather due to an alleged intransigent attitude by the shipbuilder. This pride of authorship has· no place in a professional engineering environment; if the \Wrding of a specification has proven unsatisfactory in the past, instead of pointing the finger of responsibility at some other party, the wording should be changed, based on a *lesson-learned* analysis of the disaster or near-disaster.

9.3.14 Technical Documentation Requirements

In addition to the hardware of the ship itself and spare parts, Purchasers usually require substantial, supporting documentation. This documentation is additional to the certificates from regulatory agencies and classification, which have been described in Table 9.IV, with a sample listing of them.

Some of the required documentation is short-lived, such as megger readings after installing (pulling) electrical cable or steel and air temperature readings when applying coatings. Once ship construction and testing is satisfactorily completed, no one will be interested in that documentation. Other components of the documentation are long-lived, such as the sea trial results for all the machinery, forming a lifetime engineering database for those items. Examples of the types of documentation which may be required are listed in Table 9.VII.

The development of each of those items of documentation represents additional cost to the Contractor. Some of those documentation items may be generated by the Contractor or its naval architects and design engineers in the course of obtaining regulatory and/or classification approvals. For those documentation requirements which are not needed for such purposes, the Contractor cannot be expected to prepare them unless the need for them is clearly stated in the Contract Specifications, or in the Agreement, so that they can be included in the Contractor's budget. Even for those documentation items generated in the course of obtaining regulatory and/or classification approvals, the Contractor may not be obligated to go the extra step of providing them to the Purchaser unless they, too, are identified in the contract documents as being *deliverable* to the Purchaser. If any of those documentation deliverables are to be provided to the Purchaser in computerized form, the Contract Specifications should clearly state that requirement in order to avoid disputes over interpretation of what constitutes usual practice.

9.3.15 Common Problems with Specification Language

The work scope of shipbuilding contracts is sometimes beset by problems with grammar and word usage. The idea of using a common language between the Contractor and Purchaser is to ensure complete understanding. Contract documents between, say, a European shipowning organization and an Asian shipbuilder may be in English because both parties are reasonably fluent in English as well as their own language, but not fluent in the other party's language. Once a common language is selected, it is important that both parties use it in the same, correct manner.

Significant problems have arisen over colloquial word usage when involving two parties that both use English. For example, when a project involves a British naval architect and an American shipyard; both parties speak English as their native tongue, but in fact the colloquialisms that each use sometimes have significantly different meanings. For example, Americans *pull* cable when installing it, whereas the British *pull* cable when removing it. The point made here is to avoid colloquialisms for which others may not have the same working definition.

Words and phrases such as *workmanlike, first-class marine practice* and *good shipbuilding practice* cannot be relied upon and should generally be avoided. The very subjective nature of these phrases, coupled with the differing perspectives and expectations of the Purchaser and Contractor, effectively renders such phrases useless; they do not adequately support the Purchaser's interests or bind the Contractor to any meaningful extent.

The words *any* and *all* are not equivalent. *Any* is an indeterminate number or amount, which may mean one, some or all. It is usually better to use *all* or *any and all* to preclude the shipyard from misconstruing the work scope. In ship repair, phrases such as *as necessary, as required, to suit* and *as directed* must be used with extreme care in order to avoid ambiguities. Those phrases do not lend themselves to development of estimates of quantities, which is basis of a bid and contract. In cases where the extent of repairs cannot be known beforehand, the specification should be carefully drawn and a procedure should be implemented to handle open and inspect items and other conditional work.

TABLE 9.VII Examples of Documentation Required by Shipowner for New Ship Construction

Hull Model Test Results	P.O. Technical Specifications
Propeller Model Test Results	Responses to comments on drawings
Propeller-induced Vibration Studies	Finite Element Analyses
Preliminary Weights and Centers Reports	Fatigue Analyses (Structural)
Preliminary Trim, Weight and Stability	Heat Load Calculations
Final Weights and Centers Reports	Electrical load Calculations
Final Trim and Stability Reports	Fault Current Analyses
Damage Stability Analyses	Inspection Deficiency Reports
Tank Capacity Tables	Responses to inspection Reports
Correspondence with Classification Organization	Temperature/Humidity during coatings
Correspondence with Regulatory Agencies	Megger readings (electrical cable)
Detailed Initial Schedule (engineering, procurement, production and testing)	Noise Level Readings
Updated Schedules as appropriate and per contractual requirements	Test Results (numerous types)
Working Plans	Vibration readings
Detailed Drawings	Crane and Trolley Test Results
Production Sketches	Dock-trial Test Results
Drawings submitted to Classification	Sea-trial test Results
Drawings submitted to Regulatory Agencies	Operational Placards on the Bridge
	Safety Placards throughout the ship
	Progress photographs
	Component Manuals
	System Manuals
	Final photographs
	As-built (as-fitted) Drawings

9.3.16 Shipowner-Furnished Equipment

The decision by the Purchaser to supply shipowner-furnished equipment (OFE) to the Contractor for installation aboard the new ship may be based on any of several possibilities:

- long lead time procurement requirements,
- already-stocked by the shipowner's organization,
- absolute control over equipment selection;
- potential savings, and
- easier procurement than by shipyard, among other possible reasons.

Regardless of the motivation and/or reasoning by the Purchaser, which results in the use of OFE, none of them can guarantee a risk-free relationship between the Purchaser and the Contractor.

The incidence of disputes and/or misunderstandings associated with OFE is far too common to dismiss as an aberration. Rather, analysis of past OFE-related disputes indicates that there are six aspects of OFE that often are not adequately addressed in the specifications, thereby causing disputes and/or misunderstandings: content, form, place of delivery, schedule of delivery, vertical integration, and horizontal integration.

Each of these elements of OFE are discussed herein to promote an understanding of the potential problems that must be circumvented by appropriate specification language.

The content of the OFE needs to be defined with sufficient precision so that the Contractor knows what is and what is not being provided. The Contractor will be responsible for supplying all ofthe necessary fixtures, fittings and connections that are necessary to incorporate the OFE into the ship; but the Contractor must base its bid price on an understanding of what hardware it has to provide. Consideration of the interface hardware provides examples: foundations; conversion fittings (metric to imperial units); connector cables and hoses; and resilient mountings; among others. Some Purchaser's have supplied the entire propulsion system as OFE, in which instances questions arose over which shaft bearings and which foundations were also to be OPE. One shipowner thought the rudder and its control mechanism were part of the propulsion system that was being purchased separately from a vendor. Other shipowners have mistakenly thought that the governor is always part of the shipowner-supplied diesel engine; this is not necessarily correct. These examples are mentioned to illustrate that what is going to be supplied as part of the OFE may be obvious to one party may be far from obvious to another.

The form in which OPE will arrive at the shipyard should be communicated to the Contractor by the specifications to ensure that all costs and schedule impacts arising from the OFE can be included in the bid price. The extent of assembly work that will be required if the OPE arrives in pieces is important to the Contractor. The need to provide temporary protective covering or other maintenance services prior to shipboard installation may also be a cost basis to the Contractor. Any other aspects of the form of OFE that may require labor or materials to prepare the OPE for shipboard installation should also be addressed in the specifications.

The place of delivery of OPE is usually addressed in the Agreement, such as the Contractor's warehouse at a specific street. However, if it is not addressed in the Agreement, the point of delivery should be included in the specifications. If some of the OFE is being delivered at a near-by seaport or airport, and other OPE is being delivered to the shipyard, that differentiation should be made. If the Contractor has to provide transportation of the OPE from a remote (non-shipyard) location, the Contractor may wish to include those costs in its bid price (drivers, insurance, truck rental, etc.).

The Contractor is usually required, per the Specifications, to provide to the Purchaser a report on the condition ofthe OFE upon its delivery to the shipyard, identifying any damages or unexpected conditions. The Purchaser is usually responsible for correction of those damages or conditions, and the Contractor becomes responsible for any subsequently noted damages.

In order to plan the work appropriately, the schedule of delivery of OFE must be communicated to the Contractor if it is not already stated in the Agreement. If the schedule of delivery is not identified by the contract documents, it may be established by the Contractor and communicated to the Purchaser through development and transmittal of the detailed project schedule. If this occurs, the Purchaser may face OFE delivery commitments that cannot be achieved, in which case the Purchaser must advise the Contractor of more appropriate OPE delivery schedules before the project is substantially underway.

Vertical integration of OFE refers to the process of integrating each item of OFE with all those parts of the ship which the Contractor has responsibility to supply. This integration may include consideration of piping and electrical connections, air and exhaust connections, fuel and lube oil supply, water and steam connections, the structural foundation, as well as the control, alarm and monitoring systems. Before the physical integration takes place, the design integration requirements have to be addressed by having the Purchaser supply to the Contractor all relevant connectivity and interface information. The vertical integration also addresses the need for component, system and ship testing as appropriate. The Contractor will need to know, for scheduling purposes, if the vendor's technical representative will have to conduct independent tests to ensure proper installation as a basis for issuing the vendor's warranty.

Horizontal integration of OFE refers to the process of integrating each item of OPE with other items of OFE, as appropriate. When the Purchaser is supplying multiple components of a system as OPE, responsibility for the compatibility and connectivity of all those components with one another usually rests with the Purchaser, not the Contractor. For example, if the OFE includes a diesel engine as well as a torsional coupling, the compatibility of the physical mating of the torsional coupling to the engine's flywheel may have to be assured by the Purchaser, not by the Contractor. If hydraulic cylinders as well as a hydraulic power pack are being supplied as OFE, the hydraulic, electrical, control and alarm connections between them need to be addressed, since the Contractor may otherwise believe that the Purchaser is supplying and arranging for all those connections to be completed by the vendor of the equipment.

Accordingly, specification writers must thoroughly investigate, understand and communicate in the written Contract Specifications all aspects of OFE that may cause the Contractor to incur costs and/or schedule impacts. If any assumptions have to be made by the Contractor to price the OPE-related work, the specification writer should realize that the assumptions will be "least-cost" ones, placing a greater burden on the Purchaser and the vendors of the OFE, at the expense of the Purchaser unless clearly stated otherwise in the Contract Specifications.

9.3.17 Identifying Necessary Tests and Trials

The process of conducting any test or trial represents a cost to the Contractor. In order to prepare a complete bid, the Contractor has to know in advance the nature and extent of all tests and trials that need to be conducted. Thus the Contractor must be able to ascertain from the contract documents, primarily the Contract Specifications, both the nature and the extent of the required tests and trials. The necessity for tests may originate with regulatory agencies, classification organizations, the Purchaser's additional requirements, or the OFE vendor's requirements.

Many of the tests and trials will have to be conducted to satisfy the regulatory requirements and the classification rules. If, as is customary, the Contractor is solely responsible for obtaining all regulatory and classification approvals, the Purchaser need not spell out each and every such test that is within that part of the work scope. However, if the Agreement doesn't already state it, the specifications should clearly state that the Contractor must perform all inspections and tests necessary to obtain all the approvals and certificates from the various regulatory agencies and the classification organization that are listed elsewhere in the contract documents, all at no additional cost to the Purchaser.

The more challenging aspect of this section of the specifications is to address the Purchaser's additional test requirements and the OPE vendor's test requirements that are supplementary to the other, already-addressed tests and trials. There is no nearly universal set of tests that falls within this category. Every ship type has differing requirements, and within each ship type, every Purchaser will have differing requirements. The Purchaser's and OPE vendor's test and trial requirements are shaped, in part, by their perception of what is needed above and beyond the regulatory and classification tests and trials. It should be noted that the duration or extent of tests and trials is also an important cost factor to the Contractor. If, for example, there is special equipment aboard the ship due to its particular shipowner and mission, some Purchasers may require a full 24-hour heat run, and others may be content with a 4-6 hour test; the Contractor must know the extent of those tests and trials in advance of bidding, perhaps by references to appropriate SNAME, ASTM, or other standards and procedures.

9.3.18 Compartment Closeouts

During the process of ship construction and testing, every component and system will have been tested, all the structural work will have been inspected, and all of the coatings, deck finishes, and overhead closures will have been inspected. However, those inspections and tests will have taken place while the shipyard personnel were still active in each space or working on each deck area, and while shipyard equipment was still widely distributed throughout the ship. Compartment closeouts are the inspection activity by the representatives of the Purchaser to confirm that the shipyard has cleaned-up and withdrawn from each compartment prior to ship delivery.

For these purposes, a compartment is any of the following: tanks, void spaces, each level of sections of cargo holds between deep web frames or bulkheads, control rooms, equipment rooms, reefer spaces, store rooms, accommodations, heads, galleys, sections of passageways, chart room, interior bridge, bridge wings, steering gear flat, paint rooms, chain lockers, shaft alley, each level of each of the machinery spaces, bosun's locker, each section of the weather deck, and every other type of area that may be appropriate to the individual ship.

This section of the Contract Specifications could require the Contractor to prepare each such compartment for a joint inspection after the shipyard has completed and withdrawn from each compartment. This would include, but not be limited to, removal of scaffolding and ladders, withdrawing of welding leads and gas hoses, removal of temporary lighting and ventilation, paint touch-up where temporary clips have been removed, picking up papers, cans, welding rod stubs and other disposables, clearing out all bilge suctions, disposal of all temporary protective materials, and confirmation of the placement of labels on cables and piping, if required by the specifications, among other possible aspects of these compartment close-out inspections.

To avoid having the Contractor present all the compartments on a ship for close-out inspection at the same time, the specifications could require the Contractor to present in advance a list of all the compartments and a proposed close-out inspection date within a few weeks prior to vessel delivery, which schedule would be subject to negotiation if needed. Certainly many of the compartments can be closed out prior to sea trials, and the remaining ones closed out in orderly fashion between the conclusion of sea trials and Vessel Delivery.

9.3.19 Disposal of Hazardous and Toxic Materials

The process of ship construction may occasionally create waste materials that are deemed hazardous or toxic according to environmental regulations. For example, in some jurisdictions, empty but wet paint cans are hazardous materials. Ordinarily, the Contractor will be solely responsible for the proper transportation and disposal of any toxic or hazardous materials resulting from the construction process.

If the delivery to the shipyard and installation of OPE creates any toxic or hazardous materials, the handling, transportation and disposal of them has to be carefully addressed by the Contract Specifications. First, the specifications have to identify them by type, constituents, and quantity. Second, the specifications have to assign to the Contractor the responsibility for containing those materials to prevent contamination of the shipyard or the ship itself. Third, the specifications must call for the Contractor to provide safety and health appliances for employees as may be appropriate and consistent with health and safety regulations. Fourth, the specifications then should address the need to transport those materials over public highways by carriers who are licensed to do so, and fifth, to dispose of the materials at landfills, incinerators or by other means at facilities that are licensed to undertake such disposal, all at no additional cost to the Purchaser.

9.3.20 Work Performed by OFE Vendors

When the vendor of OFE sends a technical representative *(tech rep)* to the shipyard to direct or oversee the installation or start-up of OFE, the Contractor may have to provide support services to that tech rep. These services may be limited to the provision of temporary lighting and ventilation or scaffolding and ladders. Sometimes the OFE vendor's tech rep may require the assistance of several of the shipyard's mechanics or other craftsmen for a period of time.

For each instance where the OPE vendor's tech rep will require shipyard support services, the rendering of those services will be a cost to the Contractor. Accordingly, the Contract Specifications could advise the Contractor of the need to provide such support services and indicate the nature and duration of the manpower and equipment needed for such support services. If this matter is not adequately covered by the Contract Specifications, the Purchaser may be asked later for a Change Order to cover those costs.

9.3.21 Facilities for Shipowner's Representatives

Most shipyards have rooms in their office buildings set aside for use by the Purchaser's representatives during the design, construction, testing and trials phases of the ship construction project. Some shipowners' organizations require more space than others, and some require particular equipment to be provided within those facilities. Unless the contract documents, usually the Contract Specifications, indicate the type, size and furnishing of the facilities, 'only minimal facilities may be provided, if any.

Thus, this section of the Contract Specifications should indicate the requirements for each of the following:

- total area to be provided,
- number of different rooms within that total area and approximate area of each room,
- the fact that the rooms should be located contiguous to one another,
- the number of desks and chairs to be in each room,
- the capacity of the conference table (if required),
- the size and number of drawing tables,
- the number of telephone lines in each room and number of connection points for each,
- the total number of telephones to be provided,
- the total number of fax machines to be provided,
- the presence of a xerographic copier of a nominated copying rate and document reproduction size,
- other features that will facilitate the obligations and work of the Purchaser's representatives, and
- proximity of the offices to the ship before launching.

For reasons of security, if considered appropriate, the specification could require that the phone and fax lines for those offices be run directly from the street and not go through the shipyard's centralized phone system. (Cellular phones are not a form of secure communications.) For reasons of convenience, the specification could require the shipyard to temporarily provide a certain number of pagers for use by the Purchaser's representatives.

9.3.22 Development of Contract Plans

Throughout this section on Formation of Contract Specifications and Plans, the emphasis has been on the wording of the Contract Specifications, and only occasionally have the Contract Plans been mentioned. This is not to lessen the importance of the Contract Plans, but rather recognizes that the Contract Plans are usually considered to be part of the Contract Specifications, or at least to be below the Contract Specifications in the hierarchy discussed in Section 9.2, on Formation of the Agreement.

The purpose of Contract Plans is to convey to the Contractor the spatial relationships, the configurations, the arrangements and the appearances of the various parts of the vessel that are not capable of being conveyed solely by written words. By identifying them as Contract Plans, the intent is that they are non-alterable except by a formal Change Order.

The contract-level design expressed in part by the Contract Plans can vary considerably; some contract-level designs will include only a few drawings and be sparse with details; others will include a large number of drawings, each of which contains considerable details.

From the outset of the project, the Purchaser and its naval architects and design engineers have to decide what design configurations pertaining to the ship must be controlled entirely by the Purchaser (these become the Contract Plans), what design configurations can be determined from regulatory and classification requirements, and what design configurations can be determined by the Contractor so long as they satisfy all other contractual requirements. The phrase *design configurations* is used here because that is the type of information that is best contained in plans rather than specifications. In other words, development of the list of drawings that will be Contract Plans is the output of a risk-decision analysis. If the configuration of a certain aspect of the ship is not included in a Contract Plan, the final configuration will be determined by the Contractor in its search for a least-cost solution.

If the presence of inclined ladders in a particular area of the ship is important to the Purchaser, for example, when regulations would otherwise permit vertical ladders, that requirement may be best communicated to the Contractor in a Contract Plan. The shape of the hull may be considered too important to be left to the discretion of the Contractor; but if the vessel is a low-speed barge, only general guidance as to the bow and stem configuration may be necessary, thereby allowing the Contractor to design it as a least-cost solution.

Once a decision is made as to what information will be conveyed to the Contractor by the Contract Plans, the Purchaser's naval architects and design engineers must ensure that the Contract Plans are not misleading. For bidding purposes, the Contractor is allowed to rely on information contained within the Contract Plans as being consistent with the nominated regulations and classification rules. If, for example, the Contract Plans include a schematic ventilation plan showing 14 fire dampers, the Contractor is allowed to rely on the fact that only 14 fire dampers will satisfy regulatory requirements. If a lesser number is required, the Contractor is still obligated to install the indicated 14 fire dampers; but if a greater number is required, the excess above 14 may become the basis of an essential Change Order.

Tolerances that are to be achieved are often implied by reference to a standard, in which case the standard should be reviewed for applicability before citing it. However, if tolerances for certain elements of the ship are of special concern to the Purchaser, they should be expressly stated in the relevant Contract Plans or Contract Specifications. For example, the tolerances within cell guides for container ships may be different from normal shipbuilding standard tolerances.

9.3.23 Interpretation of Contract Plans

In order to avoid misunderstandings that arise later, it may be advisable for the Purchaser's naval architects and design engineers to seek regulatory and/or classification approvals of the anticipated Contract Plans before the contract is executed. Problems have arisen in the past due to the fact that the Purchaser's naval architects did not interpret the classification requirements in the same manner as the classification organization itself. Pre-contract approval of the Contract Plans, however, does not eliminate the need for further approvals of the more-detailed plans that are to be developed by the Contractor after contract execution.

The Purchaser's naval architects and design engineers should appreciate that many objects shown on Contract Plans are representations only, and do not indicate with precision the dimensional proximity of structures or other items of equipment. This means that the Contractor will have a *window* of placement of that item of equipment. If clearances around that item of equipment are important, it would be best if the drawing noted that requirement, possibly with reference to an appropriate Contract Specification item.

Both parties have to recognize that the notes contained within a drawing are as much a part of that drawing as are the graphical representations. If the note states that the dimensions and linear weight of a stiffener is *typo* or typical for a group of stiffeners, the Contractor cannot pretend that the information was lacking. On the other hand, the Purchaser's naval architects need to appreciate that shipyard personnel cannot read the minds of the persons preparing the drawings. Thus, the working rule should be that if there is any doubt as to how someone other than the author of a plan will interpret part of it, then more information is better than less and more notations are better than fewer, even at the risk of making the drawing look too *busy.* If it is necessary to refer to a second Contract Plan to fully understand the first, it is best to not assume the Contractor will examine both plans concurrently. Rather, the first plan could reference the second one, and vice-versa, to ensure clarity, without which risks are being created.

A previous sub-section of this section addressed the subjects of composite drawing and the resolution of interferences. Naval architects and design engineers who have not prepared composite drawings prior to the execution of the contract should anticipate that likely there will be interferences arising from a strict interpretation of the contract documents. Accordingly, those persons should be prepared to accept variations from the Contract Specifications and Contract Plans that need to be altered to eliminate such interferences. Again, it can be expected that the Contractor will seek to eliminate those interferences in a least-cost manner.

If the Purchaser's naval architects and design engineers are not going to be receptive to Contractor-determined resolution of interferences which arise from the contract documents, perhaps they may wish to undertake the development of composite drawings prior to contract execution. However, this would be meaningful only for those situations in which the Purchaser wishes to control nearly all of the spatial relationships, configurations, arrangements and appearances through the use of a large number of Contract Plans, which is fairly common for naval combatant vessels and passenger ships.

Contract Plans generally should not include quantities of materials, though they could indicate types of materials in a Bill of Materials at the top of the drawing if the types are not already identified in the Contract Specifications. The presence of exact quantities on Contract Plans may lead to allegations of extras by the Contractor, resulting in an otherwise unnecessary Change Order.

If the Contract Specifications and Contract Plans are available in computerized format, the Purchaser can provide them to bidders as long as a contractually binding hard *(paper)* copy, produced by the original developer of them and not by another party, becomes the official contract document.

9.3.24 Use of Guidance Plans

Some naval architects who develop and/or assemble the technical documents for a shipbuilding contract incorporate into the contract package several *Guidance Plans* in addition to Contract Plans. One possible reason for the differentiation between Guidance Plans and Contract Plans may be that the naval architect has in mind a different degree of required compliance by the Contractor.

Another possible reason for the inclusion of Guidance Plans is to give the Contractor a *starting point* for its own design development responsibilities. A third possible reason for incorporating two different types of plans in the contract package is to encourage the Contractor to seek alternative, lower-cost means which will lead to savings for both Purchaser and Contractor. There are several other possible reasons for including Guidance Plans in a contract package.

The realization that there may be any of several reasons for using Guidance Plans in addition to Contract Plans points out a potential cause of contractual difficulties. Namely, the Contractor may attach a different significance to the Guidance Plans than intended by the Purchaser. The means of avoiding such difficulties or disputes is to either avoid using Guidance Plans, or to define the use of the word *guidance.* For example, the phrase Guidance Plans can be defined in the Agreement to mean plans from which the Contractor ,may vary, at no additional cost to the Purchaser, only if appr6ved in advance by the Purchaser.

Another possible definition of Guidance Plans could be, for example, plans which must be adhered to in all respects except that the exact dimensions shown or implied therein may result in physical interferences with other components of the ship, which interferences are to be resolved by the Contractor at no additional expense to the Purchaser. There are, of course, many other possible definitions of Guidance Plans; but failure to define the term, when Guidance Plans are included in the contract package, may lead to confusion at best, or serious disputes at worst.

9.3.25 Newbuilding, Repair and Conversion

Although this chapter is intended to apply to new ship construction, certain aspects of it also apply to ship conversion and repair. It should be appreciated, however, that this section on Formation of Contract Specifications and Plans is least applicable to ship repair, and a slightly greater portion of it may apply to ship conversion.

For ship repair, the specifications address each repair item individually, although the general section of the Contract Specifications may be somewhat applicable to repair as well as newbuilding. Ship conversion, which involves a significant amount of new steel and/or new arrangements, may appear to be more related to newbuilding than to ship repair. However, ship conversion specifications are even more difficult to write than newbuilding specifications. The reason for that greater difficulty is that in ship construction, the specifications and plans must only define the final product, but in ship conversion, the specifications and plans must define both the starting point (the ship before conversion) as well as the end point.

These points about ship repair and ship conversion specifications are included only to caution the reader that those types of projects are quite different from new ship construction. Accordingly, the formation of Contract Specifications for ship repair and the formation of Contract Specifications and Plans for ship conversion will be a measurably different process than discussed above.

9.4 MANAGEMENT OF CONTRACTS DURING PERFORMANCE

9.4.1 Introduction

The purpose of active and responsible contract management is two-fold. First is the necessity of monitoring your own team's responsibilities and managing them through the use of your own contract management team's resources and through the timely redirection or re-allocation of those resources as appropriate. The second purpose is monitoring the other party's fulfillment of its responsibilities and notifying that party when the potential or actual failure to fulfill its responsibilities arises.

The responsibilities of each party are defined by the contract documents, primarily by the Agreement, the Contract Specifications and the Contract Plans. The preceding sections focused on the development and formation of those documents in a manner that provides a contractually-binding foundation or basis that will ensure the Purchaser gets the product it has bargained for, and the Contractor has to produce no more than it is being paid for.

With that foundation in place, the Contractor expects that it should be able to proceed with its planning, engineering, procurement, production and testing with only minimal interference from the Purchaser. At the same time, the Purchaser believes it has the right to expect that the Contractor will provide all the plans, schedules and documentation supporting the design, construction and testing in a timely manner, and expect that the Contractor will construct and deliver the ship on time.

These two sets of expectations suggest that, aside from engineering and production work, there is not much for either party to do besides watch the ship being designed and built. That perception is not only wrong, but also dangerous. In fact, there are a tremendous number of contract management activities that must be addressed by both parties during contract performance. If one party or the other takes the attitude that it shouldn't have to do much contract management now that the contract has been signed, then that party is likely to pay a severe price for not having actively managed the contract.

In other words, those are theoretical expectations, and are not fully achieved in practice. Sometimes actual practice varies considerably from those theoretical expectations due to either or both parties' mismanagement of the contract during contract performance.

9.4.2 The Origins of Contract Mismanagement

Shipowners' on-site representatives sometimes believe that the Contractor has the attitude that the shipyard will follow the spirit of the Contract Specifications and Plans, but will not always meet certain exact requirements as stated therein. This, in the eyes of the shipowners' representatives, undermines the contractual requirements and dilutes the effort that was put into defining the Specifications and Plans. If that situation is developing, shipowners' representatives must manage the contract more aggressively to get the Contractor's actions into alignment with its contractual responsibilities.

Similarly, from the shipyards' perspectives, it sometimes appears that shipowners expect the shipyard to modify the Specifications and Plans to suit certain more-costly interpretations of the shipowners' representatives, but without formally changing the Contract Price or performance period. Sometimes Purchasers' engineering staffs try to use the drawing review process to micro-manage the detail design decisions that were ceded to the Contractor. From the shipyards' perspectives, any such behavior by shipowners' representatives undermines the right of the Contractor to select the means of achieving compliance with the Specifications and Plans, all at a fixed price. If that situation is developing, the shipyard must also manage the contractual relationship with the shipowner's representatives more aggressively in order to restrain them from asking for more than they have the contractual right to do.

lt is appropriate to recall part of the introduction to this chapter:

> ... But there is another form of disaster involving ships; namely, contractual disasters, situations in which the shipyard and ship shipowner are both terribly harmed due to mismanagement of the shipbuilding contract.

It is noted that disasters result from *mismanagement of the shipbuilding contract.* This means that the contractual disasters can originate not only with poorly developed contracts, which development is part of contract management, but that contractual disasters can also evolve from improper or unsuitable management during contract performance.

In other words, situations arise in which one party or the other, Contractor or Purchaser, are not managing the contract, but instead are either expecting to maintain a relationship with the other party while operating contrary to the rules of the contract, or are simply neglecting their responsibility to actively manage their side of the contract. The risks associated with such actions are often translated into an abandonment of the rights of one party or the other in order to avoid litigation, or may result in litigation or arbitration. By developing a clear understanding of each party's contract management responsibilities during contract performance, and then fulfilling those responsibilities, both parties are assured of achieving what they bargained for during contract formation and the described adverse risks can be avoided.

9.4.3 The Contract Management Team

The actual management of the contract for each of the Contractor and the Purchaser is usually accomplished by a number of specialists who, collectively, constitute the contract management team. Depending on the size, complexity, uniqueness and schedule of a shipbuilding project, and possibly depending on other factors, too, the size of the contract management team *after the contract is executed* may be as large as several dozen individuals, as in large navy projects or cruise ships, for example, or as few as one individual occasionally aided by consultants, as in a small pilot boat, for example.

Some shipowners undertake a sufficient number of shipbuilding contracts to warrant having a full-time staff of contract management specialists; and other shipowners use an outside team of specialists or consultants. Usually a shipyard's contract management team consists of its own staff members, but occasionally the shipyard will utilize specialist consultants if the ship type is unique or new to the shipyard, if the shipyard is experiencing a temporary surge of business, or to mitigate risks when contracting with certain shipowners.

Regardless of the type and size of the Purchaser's contract management team, it is important that the remainder of the Purchaser's organization give prompt, effective support to the team whenever such needs arise. If there is any shipowner-furnished equipment, the most important group to provide support will be the shipowner's purchasing department. A lack of expediency and/or accuracy in ordering the OFE can easily result in major contract problems.

Sometimes the additional support from the Purchaser's organization may be the timely need for information from the vessel operations department, or it may be to consent to the temporary use of specialist consultants when dealing with some particular design or construction problem. Another form of support for the contract management team may be the need for approval from senior management of the deferral of changes requested by the operations department until a subsequent drydocking or ship repair period in order to cease requesting change orders from the Contractor near the end of the construction phase.

9.4.4 Effective Management

An important question on which to focus at the outset of a shipbuilding project for both shipyards and the shipowners is: how will the success of the contract management effort be measured? Some contract management teams have waited until the project was completed, and then with hindsight considered how much the budget grew during the project and how much later than the original contract Delivery Date the ship was delivered. For some organizations, that may be an acceptable form of measurement, but it does not lend itself to actually managing a contract; rather, the participants having that perspective are essentially observing developments, not managing a contract.

A more appropriate means of measuring a contract management team's performance is to have regular opportunities to alter the emphasis and re-allocate resources being applied to the contract. This is comparable to a ship navigator's course correction at regular intervals. In that situation, the navigator determines the ship's actual position relative to its anticipated position at that time, and then establishes the new, corrected course and speed which should get the vessel to its objective in a timely manner.

Similarly, the contract management team for both the Purchaser and the Contractor establish waypoints in each of the functional areas that are discussed below. Periodically, the actual contract progress in each of those functional areas is compared to the *baseline* or *planned* status that should have been achieved by that time. If appropriate, the team can then reassign resources within those functional areas that appear to be impacting or close to impacting the project. This applies to the contract management teams and resources for both the Contractor and the Purchaser.

9.4.5 Managing the Entire Contract

In this chapter, the importance and the role oftechnical persons in formation of the Agreement, as well as in the formation of the Contract Specifications and Contract Plans, has been discussed and emphasized. Too often, however, the contract management team focuses on management of the Contract Specifications and Contract Plans, and leaves aside management of the Agreement. Perhaps this situation arises because the Agreement looks too *legalistic* or has been modified and formatted by attorneys. Nevertheless, the entire contract has to be managed, including the Agreement as well as the technical aspects of the contract documentation. The business managers and lawyers of the two contracting parties are not involved in the daily contract management tasks. Thus, abandoning to organization's business managers or lawyers the management of the Agreement is equivalent to not managing the Agreement at all. That is, if the contract management team does not manage the Agreement as well as the technical documents, then the Agreement will not have been managed, creating unnecessary risks and likely incurring unnecessary costs.

A maritime industry contract management -training program (3) usually starts in the following manner: *"Read the Contract. Nearly every answer you may need, regardless of how the question is phrased, isfound in the Contract."*

Of course, the Contract includes all of the contract documents, including the Agreement. Many of the answers needed during the project are found in the Agreement but not in the technical documents. Accordingly, members of the contract management team should familiarize themselves with the table of contents of the Agreement, so that when questions arise, they can easily refer to and study the relevant sections of the Agreement as easily as they do with the Contract Specifications.

9.4.6 Contract Management Phases

There are numerous non-maritime books on contract management, but a reader of them from the maritime industry has to be aware that actual contract management practices vary between industries. Thus, the direct adaptation of the recommendations of generic contract management books may create difficulties within the maritime industry. A directly relevant paper, *A Shipowner's Management of Ship Construction Contracts* (5), addresses shipbuilding contract management from a shipowner's perspective.

That paper views shipbuilding contract management in five phases:

1. pre-contract management functions,
2. early management functions,
3. continuous Management Functions,
4. intermittent management functions, and
5. later management functions.

As illustrated in Figure 9.4, those phases occur at various times relative to project initiation, contract execution, physical construction, ship delivery, and end of warranty.

Within those five phases of contract management, the cited paper lists a total of 38 managerial activities relevant to many shipbuilding contracts. Although that paper is written from a shipowner's perspective, it is recognized that shipyards have reciprocal or initiating functions associated with each of those shipowner's management activities. A brief description ofthose 38 management activities is given in the *Appendix* to this chapter.

The progress of nearly all aspects of a shipbuilding project can be tracked by the communications between the Contractor and the other parties, including the Purchaser, regulatory agency and classification organization. Nearly every step of progress is accompanied by a communication from the Contractor, and followed-up by a communication from one of the other parties.

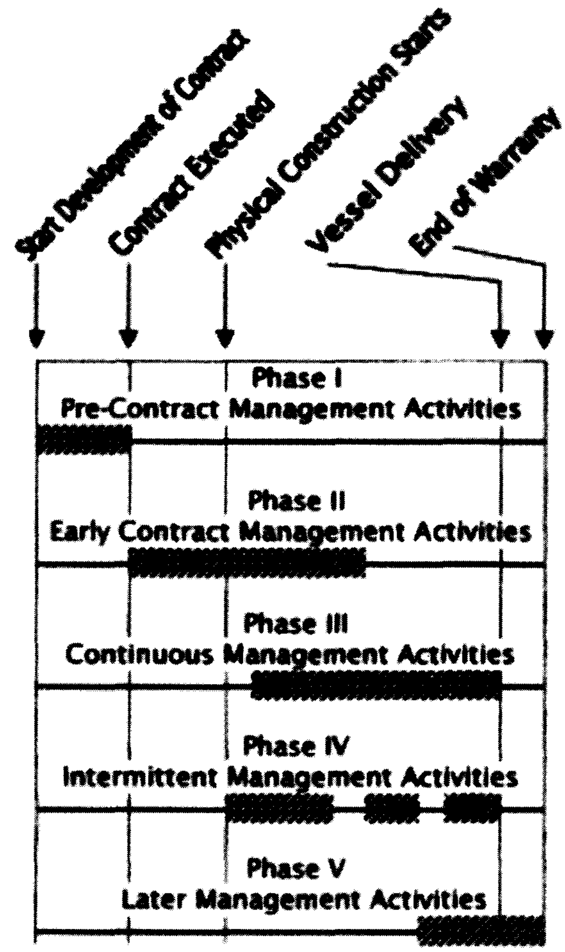

Figure 9.4 Five Phases of Contract Management

9.4.7 Contract Communications

Equally, if there is any shipowner-furnished information, equipment or materials, the delivery of such items to the shipyard is also accompanied by a communication. Thus, tracking the actual communications will create an understanding of the status of each aspect of the project. Both the Contractor and the Purchaser can employ this fundamental mechanism. For example, if the Contractor is producing detail drawings that are to be reviewed by the Purchaser in advance of construction, the transmittal of those drawings is the communication that evidences the status of the Contractor's design development. If the Purchaser then sends comments pertaining to those drawings to the Contractor, the transmittal of those comments is the communication that evidences the Purchaser's review of the design development.

As another example, if there will be some shipowner-furnished equipment (OFE) as part of the project, its arrival at the shipyard will result in a delivery receipt and possibly an inspection report upon opening of the crate. Since both parties, Contractor and Purchaser, will get copies of both the receipt and the inspection report, those communications serve to evidence the arrival of the OFE and its condition upon arrival.

9.4.8 Functional Areas of Contract Management

In order to create an orderliness out of the hundreds or thousands of communications that will be created during a shipbuilding project, the communications can be divided into functional areas, as illustrated in Table 9.VIII. The status of each of those functional areas generally can be determined with adequate accuracy by tracking the communications between the parties pertaining to each of those functions.

9.4.9 Contract Management Procedures

The tracking of communications to monitor the status of each functional area is the first step in active contract management during contract performance. Recall the analogy, above, to the ship navigator's course corrections. The first step was to determine the position and current course of the ship.

Similarly, the status of the contract work, in each functional area, including both the Contractor's and Purchaser's roles, can be reasonably determined from the communications being tracked.

The second step in the previously stated navigator's analogy is to determine where the ship should have been at the time of measuring its actual location and course. In contract management, a review of the project's schedule and the anticipated status of each functional area relative to that schedule serve to establish the progress that should have been made since the last *course correction.* This assumes that the project schedule has sufficient detail, is a valid representation of all activities in the project (engineering, purchasing, production and testing), and is not merely a *showpiece* prepared to satisfy a contractual requirement.

In the analogy, as the final step, the navigator would then determine how the ship's course and speed should be adjusted in order to assure timely arrival at the intended destination, if possible. Similarly, the contract management team considers the difference between the actual status in each functional area and the intended status at that same time, and then evaluates what reallocation of resources are appropriate to correct any untoward variations.

Of course, even without reference to communications, the Contractor tracks the actual physical progress of the ship construction relative to the planned and updated schedule. Whenever a discrepancy arises between actual and the latest-planned schedules, the Contractor must evaluate whether that schedule slippage will have any subsequent impact on ship delivery or the availability of resources that may be in short supply, such as, having a limited number of workers in a particular craft available for the project. The Contractor may then redirect the use of its resources to avoid the developing impacts.

This process of *course correction* is equally applicable to both the Contractor and the Purchaser. For example, relating to the Contractor, if it is determined that electrical installations are falling behind schedule, the shipyard would consider how to temporarily increase the rate of electrical installations by assigning more electricians or by the judicious use of overtime, among other possibilities. The,Purchaser may have similar responsibilities. For example, if the review of detail drawings by the Purchaser's engineering consultants or staff is not keeping apace with the shipyard's submittal of them, in order to not lose the right to timely comment on the drawings, the Purchaser would consider a temporary increase of the drawing review staff.

9.4.10 Functional Spreadsheets

The generally described contract management procedures rely on both the Contractor and the Purchaser having an expected status or target against which to measure the actual status in each functional area identified in Table 9.VIII. Many of those targets can be developed in both form and content in advance, and the form of others can be developed in advance but completed as to content during contract performance. For example, an advance drawing schedule identifies each of the drawings, and the target date for completion of each, that the shipyard will develop to suit its needs. Also, the shipyard will have a detailed planned schedule developed in advance for construction and testing.

TABLE 9.VIII Functional Areas of Contract Management

Drawings
Equipment Purchase Orders
Engineering Analyses and Reports
Weight Control
Schedules
Classification
Regulatory Authority
Owner Furnished Information
Owner Furnished Equipment (or Materials)
Secondary Contracts
Change Orders
Inspection by Shipowner
Inspection Deficiency Reports
Test and Trials
Invoices and Progress Payments
Spare Parts and Hardware Deliveries
Paper/Computerized Deliverables
Warranty Items

The content of some functional areas cannot be defined in advance. For example, the number and subject of inspection deficiency reports cannot be anticipated, but the means of communicating about such deficiencies can be planned in advance.

The anticipated and the routine contract management procedures for ship construction are achieved with the aid of spreadsheets in each of the functional areas that pertain to the particular project. Some contract management teams use checklists, but it is recognized that a checklist is a limited form of spreadsheet, not suitable for easy updating and the addition of other information. A spreadsheet, on the other hand, whether manual or computerized, allows for multiple data entries for each line item.

As an example, the column headings for a spreadsheet for inspection deficiency reports (I.D.R.'s) are listed in Table 9.IX. Upon inspection, if the shipowner's representatives identify a deficiency relative to the Contract Specifications or Contract Plans, an I.D.R. is sent to the Contractor.

The Contractor may acknowledge that it constitutes a deficiency and correct it then or at some other time; the Contractor may dispute that it is a deficiency; or the Contractor may offer a credit if correction of it is waived by the Purchaser.

The spreadsheet has to be capable of addressing each possible outcome, as well as have as its final column the date of closeout, when the issue was resolved between Contractor and Purchaser due to either correction or waiver-with-credit. Any special retainages associated with the deficiency are noted in the same spreadsheet.

Thus, at a glance, the contract management team for either Purchaser or Contractor will know the status of all the identified I.D.R.'s. This forms a status report that both parties can use for continuing or concluding the management of that functional area.

As another example, nearly all of the inspections to be performed by the shipowner's representatives can be listed in an inspection spreadsheet long before actual construction commences. The approximate target date of such inspections can be inferred from the Contractor's detailed schedule. The spreadsheet then performs two functions: 1. it ensures that the shipowner's representatives do not overlook any intended inspections, and 2. it tracks the timeliness of the Contractor's preparations for inspections.

Similar use is made of all the other spreadsheets developed for each of the other functional areas listed in Table 9.VIII as well as any other functional areas appropriate to the specific project.

TABLE 9.1X Spreadsheet Column Headings for Inspection Deficiency Reports

I.D.R. Number
Date of Inspection
Specification Item Number
Date Acknowledged by the Shipbuilder
Intended Correction date by Shipbuilder
Date of First Reinspection if Not Final
Date of Second Reinspection if Not Final
Date Disputed by Shipbuilder
Amount of Credit for Waiver
Amount of Special Retainage
Date of Closeout

9.4.11 Active versus Passive Contract Management

The theme of this section on the Management of Contracts During Performance is captured by a principle of contract management stated in (3):

"Both parties to a contract must be active participants during peiformance; passive contract management is taxed, active contract management is rewarded."

It was noted above that passive contract managers are no more than observers of the project's events, having no influence on any adjustment in how the responsibilities of each party are being fulfilled. However, once a decision is made instead to be active contract managers, mechanisms have to be developed to measure the success of that active contract management. As discussed in the prior section, the use of spreadsheets, either manual or computerized, associated with each applicable functional area has been found to be an effective means of monitoring the effectiveness of such management.

The initially developed spreadsheets constitute the targets for performance by both the Contractor and the Purchaser. The up dating of the spreadsheets establishes the actual point of progress in each functional area. Noting the difference between target and actual progress, the relevant party can redeploy or reallocate its available resources, or supplement those resources if appropriate, to get the project back on course to the extent needed.

It should not be forgotten however, as quoted earlier from (3), that *"Contract management should commence the moment a contract is contemplated, not after it is signed."* As discussed in the prior subchapters on formation of the key components of the contract, that stage of contract management is the most important, as it creates the contractually-binding foundation for all subsequent participation by both parties.

9.5 REFERENCES

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9.A APPENDIX

9.A.1 Shipowner's Contract Management Activities

The following constitutes a brief description, from a shipowner's perspective, of each of the activities of contract management, divided into the five phases of contract management identified in Section 4. These descriptions are adapted from *An Shipowner's Management of Ship Construction Contracts* (5). The activities described below start with the draft Agreement, draft Contract Specifications and draft Contract Plans. The corresponding shipyard's contract management activities, in addition to engineering, purchasing, production and testing, usually are either parallel activities or mirror images of the shipowner's activities. They are not separately discussed below.

In these descriptions, OF! indicates Shipowner-Furnished Information and OPE indicates Shipowner-Furnished Equipment, or Materials. The phrase *secondary contract* refers to a contract let by the ship shipowner to an organization other than the Contractor, but which is meant to support or supply the Contractor.

9.A.2 Phase I-Pre-Contract Management Activities

Organization-Development and structuring of Shipowner's contract management organization, including functional and reporting relationships pertaining to prime and all secondary contracts associated with the project (contractor, engineering, regulatory, classification, suppliers, vendors, services, etc.). A *secondary* contract is one between the Purchaser and a vendor or service-provider other than the prime Contractor, which secondary contract supports the project of the prime contract. Generally, the Purchaser has responsibility for the performance of the secondary contractors, and the Contractor has responsibility for the perfonrlance of the subcontractors.

Specifications-General: Review of specifications to maximize Shipowner's and Contractor's mutuality of interpretation of each party's technical responsibilities and to identify ambiguous or incomplete aspects of specifications which may require clarifications.

Specifications-Schedule: Development of specifications to supplement the Naval Architect's specifications with a section or sub-section pertaining to the Contractor's schedule development and schedule-reporting commitments.

Specifications-Tests and Trials: Development or modification of proposed specification pertaining to tests & trials as necessary to maximize pre-delivery verification of all systems and components modified by the shipyard.

Specifications-Downward Review: Coordination between specifications and contract plans to maximize consistency between those components of the contract.

Specifications-Upward Review: Coordination between agreement and specifications to maximize consistency between those components of the contract.

Communications: Review of specifications to identify all contractually anticipated communications evidencing compliance with contractual obligations by both Shipowner and Contractor. (see *Deliverables)*

Deliverables Control Spreadsheets: Development of computer-based, revisable, detailed lists and related information for each party's communications, approvals, reports, other software and hardware deliverables in hard-copy and electronically.

9.A.3 Phase II-Early Management Activities

Project Kick-Off Meeting-Meet with Contractor's contract management team to develop mutual interpretations where ambiguities exist and to discuss other administrative and procedural matters, which may be relevant to a smooth-running contractual relationship. Some of the other matters, as identified in reference 2, are:

- Avenues for exchanges of documentation and information,
- Clarify contract specifications & plans,
- Clarify precedences, inclusions, exclusions,
- Identify OF! that is needed early to get project started,
- Identify what is not already included in price & work scope,
- Identify unit prices for labor, services, lay days, material mark-up,

- Identify crafts and services that will be directly charged in change orders,
- Procedures to control shipowner property (if applicable),
- Billing and payment practices,
- Reporting requirements (weights, stability, vibration, noise, EMI, others),
- Change order procedures, including distributed, limited authority,
- Number of change order hours that automatically gives one day extension,
- Quality control, testing, inspections, compartment close-outs,
- Identify standards that will apply to key inspections,
- Turn-around times for condition reports and change proposals,
- Disposal of hazardous and/or toxic materials,
- Spare-parts requirements,
- Subcontract, or prime contract) issues,
- Where shipowner will inspect the subcontractor's work,
- Up dating & release of scheduling information,
- Special retainages for outstanding deficiencies, and
- Fire watch, fire response, pressurized fire main.

Schedule: Review of Contractor's proposed critical path network to ensure all elements of the work scope are properly included, such as completion of design, engineering, procurement, production, subcontracts, tests & trials.

CFE Procurement: Monitoring of Contractor-furnished equipment (CPE) having long-lead time procurement windows. Failure by the Contractor to allow realistic, that is, long lead times for major or specially-manufactured equipment is a too-frequent problem leading to costly repercussions in ship construction projects. For that reason, the Purchaser should consider monitoring the Contractor's ordering process and its schedule.

OFI Procurement: Procurement of Shipowner Furnished Design Information as required by contract.

OFI Schedule: Coordination with contractor for timely delivery of Shipowner-Furnished Information.

OFE Procurement: Procurement of Shipowner Furnished Materials & Equipment and associated technical information.

OFE Schedule: Coordination with contractor for timely delivery of Shipowner-Furnished Materials & Equipment.

Secondary Contracts: Management of Shipowner's secondary contracts for design, support services and any OFE or OF!.

Drawings: Receipt and review of Contractor's detail drawings, including bills of material, and preparation of comments as appropriate.

9.A.4 Phase III-Continuous Management Activities

Critical Path Network: Review of Contractor's updates of the critical path network to ensure that schedule updates reflect actual project conditions and events (start, percent complete, finish).

Progress Meetings: Leadership at regular progress meetings with Contractor and follow-up to ensure all obligations by both parties arising there from are timely satisfied.

Progress Monitoring: On-site identification of when critical path activities have started and finished to monitor Contractor's performance vis-a-vis its own planned schedule.

Progress Payments: Review of Contractor's progress invoices to ensure that all invoiced amounts have been earned.

Classification: Oversight and review of Contractor's communications with classification organization.

Regulatory: Oversight and review of Contractor's communications with appropriate regulatory authorities.

9.A.5 Phase IV-Intermittent Management Activities

Contract: Maintenance of up-dated contract including changes to price, technical specifications, contract drawings and delivery date.

Change Specifications: Development or review of technical aspects of proposed changes and Shipowner's estimate of cost of changes.

Change Negotiation: Negotiation of proposed changes after review and acceptance by technical staff.

Delays: Review of Contractor's requests for *force majeure* delays and oversight of other potential causes of delay.

Extensions: Review of contract extensions requested by Contractor in association with potential changes.

Rework: Identification and documentation of types, areas and timing of Contractor's own rework necessitated by its own errors.

9.A.6 Phase V-Later Management Activities

Inspections: Identification of work in progress and completed items to be inspected and accepted.

Deficiencies: Development of inspection deficiency reports for transmittal to shipyard and follow-up to ensure correction of cited deficiencies.

Tests & Trials: Review of draft agendas for tests and trials, oversight of tests and trials, review of final reports on tests & trials.

Acceptances: Preparation of notices of acceptance of inspections, tests and trials, and conveyance of the acceptance to Contractor.

Compartment Closeouts: Final closeout inspection of each compartment upon presentation by Contractor (includes each tank and void space as well as working spaces), and conveyance of the acceptance or deficiencies to Contractor.

Manuals: Review of draft manuals, including signs and placards, preparation of comments to Contractor, review of final manuals.

Spare Parts: Development of approved spares lists and communications with Contractor to ensure timely arrival of spares.

Delivery: Development of draft vessel delivery documentation and inventorying and filming of status of ship at time of delivery.

Warranty: Accumulation of warranty items identified by operational staff, transmittal of reports to shipyard and follow-up to ensure correction of cited warranty items.

Chapter 10

Cost Estimating

Laurent C. *Deschamps and John Trumbule*

10.1 NOMENCLATURE

Block A structural interim product made from assemblies, sub-assemblies and parts, which can be joined with other blocks to form a grand block or can be erected individually.

CER A Cost Estimate Relationship is a formula relating the cost of an item to the item's physical or functional characteristics or relating the item's cost to t \he cost of another item or group of items. Examples:
a. for steel block assembly, 25 man-hours/ton;
b. for pipe material, $25/meter; and
c. for shipyard support service, 10% production hours.

Cost Driver A controllable system design characteristic or manufacturing process that has a predominant effect on the system's cost.

Cost Risk Cost Risk is the degree of cost uncertainty within an area of a project. It can be measured simply by relating the cost estimate against potential minimum and maximum cost values or by probabilistic distributions. Cost Risk can be impacted by schedule risk, technical risk, performance risk and economic risk.

Direct Cost Any costs which are identified specifically with a particular final cost objective. Direct costs are not limited to items that are incorporated in an end product. For example, support services that can be specifically allocated toward a given project may be direct costs.

Estimate Cost figure developed to anticipate the cost for executing proposed work. The estimate normally becomes the production budget less any management reserves withheld from the estimate.

G&A General administrative costs that can be isolated from general overhead. G&A (determined more typically for government contracts) identifies administrative costs supporting the given work facility, such as legal and accounting, cost of money, marketing, etc.

Interim Product A level of the product structure that is the output of a work stage and is complete in and of itself.

Indirect Cost Costs which are incurred for common or joint objectives and which are not readily subject to treatment as direct costs. Indirect costs include overhead, G&A, and any material burden.

On-Unit Outfitting A method of installing outfit system components and equipment items into a "packaged machinery unit" prior to its installation on-block or onboard.

On-Block Outfitting Installation of systems, fittings and equipment into structural blocks have been has been assembled. This work is often called *pre-outfit.* Pre-outfit often is performed in two distinct phases: Pre-outfit hot refers to work that must be performed on the unit before the unit can be painted (steel outfit items, seats, pipe, etc.); pre-outfit cold refers to work that can be performed after the structural unit has been painted (value fitting, HVAC, electrical cabling, equipment, etc.).

On-Board Outfitting Installation of systems, fittings and equipment after the hull structure has been erected. The scheduling of on-board outfit activities normally should follow a work plan organized for Zone Sequence Scheduling.

Overhead An indirect cost that is normally related to direct labor costs. Overhead includes such general costs as employee fringe benefits, plant maintenance and utilities, rents and leases, equipment depreciation, etc.

PWBS Product-oriented Work Breakdown Structure: A combination of a number of breakdown structures that form a hierarchical representation of the products, stage and work type associated with the shipbuilding process.

Stage The division of the shipbuilding process by sequence.

SWBS Ship Work Breakdown Structure. There are many varieties of SWBS, the U.S. Navy's SWBS or more recently ESWBS (Extended Ship Work Breakdown Structure) being the most familiar. This is a system-based WBS

Unit The placement of equipment and its related systems together on a common foundation (seat) such as a packaged machinery unit.

Work Center A company department or stage of construction that is assigned specific responsibility and resources needed to perform work. Work centers may also be assigned to subcontractors.

Zone Physical areas ofthe ship: bow, stem, mid-body and superstructure. Zones can also identify structural blocks during hull construction: Bow blocks, mid-body bottom blocks, mid-body deck blocks, etc.

10.2 INTRODUCTION

Shipyards, whether doing ship repair or new construction, typically have to deal with a highly variable product or service to perform. This high degree of variation means that bidding on contracts can be extremely difficult, especially in a very competitive market. With minimal profit margins and precious little time available to make bids, the pricing of new work can be hazardous unless there is a quick and accurate means for developing reasonable and reliable cost estimates.

10.2.1 Estimating Requirements Unique for Shipyards

The civil construction industry typically bids on work after design has been completed and therefore can perform its estimating on the basis of a bill of material takeoff from drawings. Shipyard work, on the other hand, is not nearly so formalized and detailed in terms of work specifications. Ship repair contracts usually identify individual work items to be performed, but rarely with well-developed drawings available. Even new construction contracts begin without detailed production drawings. Such contracts usually include the work to develop such detailed technical information.

What usually allows a shipyard to develop rational cost estimates is its ability to catalog historical costs by some consistent work breakdown structure, or WBS. The WBS traditionally has been a list of common ship systems (hull structure and outfit, equipment, piping, electrical, paint and 'furnishings), augmented by ancillary shipyard services needed to support production. A well-known WBS is the U.S. Navy's *Ship Work Breakdown Structure,* or SWBS. Another is the Maritime Administration's *Classification of Merchant Ship Weights.* Other WBS schemes have been developed over the years by different shipyards some more detailed than others have. Regardless of the specific WBS, each provides a format by which a shipyard can collect and organize costs that can be used to estimate pricing for new work.

10.2.2 Traditional Bid Estimating

Bid estimates have usually evolved at three levels of detail. The highest level is to provide only a very *rough-order-of-magnitude* (ROM) cost estimate before any details of the ship design and manufacturing processes are fully considered. Such high-level estimates have been made on the basis of ship weight, size and other general performance parameters.

The next level is when a Preliminary Design has been prepared and system weights have been estimated, and often used to determine whether a project should be funded.

A more detailed estimate typically follows the completion of the Contract Design with a pricing process that operates within the WBS format. Traditional bid estimating usually involves several different approaches to develop the pricing information:

Hull structure is often priced on the basis of hull weight and type material (steel, aluminum, etc.). Some estimating procedures break down the hull structure into definable blocks or parts, such as double bottoms, decks, fore peak, aft section, etc. Each of these blocks has associated different degrees of production difficulty (for example, man-hours per ton) to build and therefore, different associated costs to produce. The more advanced estimating practices break down these basic hull block costs by stage of construction: preparation, fabrication, assembly and erection.

Major equipment items, such as propulsion diesel engines, are usually priced by obtaining vendor quotations, then applying estimates for labor to install and test. For long-term contracts, price adjustments for inflation and other economic effects are added.

Other outfit systems are estimated either from detail material take-off, which are rarely available for new designs, or by estimating labor or material costs on an average cost per parametric unit of issue basis. Historical costs collected by WBS can be compiled with appropriate material size parameters to provide such pricing factors if such historical data is readily available and compiled for use by the estimator.

Shipyard support services, including engineering, project management and other production support efforts (material handling, temporary services, etc.), are usually estimated as percentages of overall production man-hour costs, taking into consideration the impact of the expected duration of the contract, degree of technical difficulty, and other factors that might influence the cost for these efforts.

To complete the basis for a bid pricing proposal, overhead is estimated based upon the shipyard's production back log, which will dictate the distribution of indirect costs to the new contract. Profit depends upon anticipated aggressiveness of competing proposals for the contract and/or requirements of contract negotiations.

10.3 TYPES OF COST ESTIMATES

Cost estimating occurs at various phases of ship design development. The approach used to develop the cost estimate will largely depend upon the level of detail available for the cost estimating process.

10.3.1 Concept Design (ship type oriented)

The cost estimating possible during concept design is at a very high level and makes rather broad assumptions about the ship design, its general mission, and its physical and operational characteristics. Concept design may also make broad assumptions about the general methods and organization of the design, engineering and construction processes. This level is used to decide the economic feasibility of the project.

10.3.2 Preliminary Design (ship systems oriented)

The cost estimating during preliminary design remains at a relatively high level, but there is more detail information about the ship design with regard to the hull structure, the equipment and outfit systems. During preliminary design, cost estimating can be successfully integrated with the design-engineering process to produce high-level tradeoff studies useful for developing an appropriate direction for the ship design. These studies set the basic design parameters for meeting mission requirements within general cost and schedule constraints. Preliminary design cost estimating may begin to reflect the effects of alternate build strategies. This level is often used to evaluate and sanction projects.

10.3.3 Contract Design (interim product and manufacturing process oriented)

Cost estimating at this phase of design describes costs on the basis of production interim products (hull blocks, outfit modules, and ship zones) and manufacturing processes (preparation, fabrication, assembly, installation, testing, etc.). Cost estimating can be integrated with detail engineering trade off studies, that include not only alternatives in design, but alternatives in production engineering and manufacturing processes. The cost estimating at this stage can be used as a successful strategy for managing the detail design process and will help ensure that the final design stays within prescribed cost objectives. The costing information provides the fundamental basis for the Contract Price and for establishing production budgets. This level is used by shipyards bidding on a design rather than for design trade-off analysis.

10.4 DESIGN AND COSTING STRATEGIES

There is a number of different design and costing strategies that can impact a cost estimate.

10.4.1 Cost as an Independent Variable (CAIV)

CAIV is a Department of Defense developed strategy for acquiring and supporting defense systems that entails setting aggressive, realistic cost objectives (and thresholds) for both new acquisitions and fielded systems and managing to those objectives. The costs objectives must balance mission needs with projected out year resources, taking into account anticipated process improvements in both DoD and defense industries. This concept means that once the system performance and objective are decided (on the basis of cost-performance trade-offs), the acquisition process will make cost more of a constraint, and less of a variable while obtaining the needed military performance (1,2).

CAIV has brought attention to the government's responsibilities for setting and adjusting life cycle cost objectives and for evaluating requirements in terms of overall cost consequences. This is a shift from the traditional Design-to-Cost analytical approach.

CAIV and Design-to-Cost have the same ultimate goal of a proper balance among RDT &E, production and operating and support costs while meeting mission needs according to an established scheduled and within an affordable cost. However, CAIV approach has refocused Design-to-Cost to consider cost objectives for the total life cycle of the program and to view cost as an independent variable with an understanding it may be necessary to trade off performance to stay within cost objectives and constraints.

10.4.2 Design-lo-Cost

Design- To-Cost is a management concept wherein rigorous cost objectives (ceilings) are established (3). The control of costs to meet these objectives is achieved by practical tradeoffs involving mission capability, performance and other program objectives. Cost is the overriding criteria throughout the design development and production stages of the program.

When imposed on a program with a total cost constraint, a process of cost estimating is carried out throughout the detail design development. Cost, as a key design parameter, is addressed on a continuing basis and is an inherent part of the design development. **In** the final analysis, each system, subsystem and component must be considered with respect to its cost and its effect on the cost of the program. Often times, the principles of *lean design* are applied to these systems and components as a means to reduce their cost by virtue of simplifying the design, reducing the number of parts and making them easier and less expensive to build.

10.4.3 Negotiated Production Rates

Negotiated Production Rates is a development of time and materials type of contracting where the full scope of work is undefined. These contracts negotiate not only traditional labor rates, but also the production rates applicable to the contract being pursued. These production rates are based directly upon the shipyard's CERs measured to perform a variety of different work types and manufacturing processes. Such cost and pricing methods are used for establishing cost management of change orders and other work that cannot be identified in detail and where fixed price contracting may carry too high a risk for either the shipyard or the shipowner, or both.

10.4.4 Life Cycle Costs

Life Cycle Costs (LCC) include design and acquisition (production) costs as well as operations and supports costs throughout the life of the product. Life cycle costs have often been a major consideration for commercial shipowners who must look at *the bottom line* for profit and a return on their investment. If the cost of design and construction, including the cost of money, cannot be recouped within a reasonable amount of time, the ship will not be built. If the operating and maintenance costs (plus amortized construction costs) exceed operating revenues, again the ship will not be built.

When viewing the life cycle cost breakdown, only about 25% of the costs may be directly related to acquisition (4). That means 75% of the total cost is operation and support and is made up of personnel, maintenance, and modernization. For naval ships, the largest of these (37%) is personnel cost, followed by maintenance (21%) and modernization (13%).

Therefore, in order to obtain a more complete picture of the overall cost of a ship, its life cycle costs may need to be estimated and evaluated. The life cycle of a ship or a piece of equipment is divided into essentially four stages: ,

Conception stage: All activities necessary to develop and define a means for meeting a stated requirement. For ships and equipment, this normally includes research and development, design, contract specifications, identification of all support necessary for introduction into service, and identification of funding required and managerial structure for the acquisition.

Acquisitions stage: All activities necessary to acquire the ship and provide support for the ship and equipment identified in the conception stage.

In-Service stage: All activities necessary for operation, maintenance, support and modification of the ship or equipment throughout its operational life. The in-service stage is normally the longest stage.

Disposal stage: All activities necessary to remove the ship or equipment and its supporting materials from service.

In order to determine the overall life cycle cost for a ship, costs must be estimated for each of the above stages.

10.4.5 Total Ownership Costs

An extension to LCC is the Navy's *Total Ownership Costs* (TOC). TOC covers the same cost elements of life cycle costs, but also includes the added costs for the infrastructures required to support training facilities and other activities normally treated as indirect costs to the ship and its operations.

10.4.6 Return on Investment (ROI)

ROI measures the estimated costs against estimated revenues. The balance or profit margin for the shipowner can make or break a design proposal. It also can form the basis for a design optimization strategy and tradeoff effort that seeks to maximize the shipowner's return on investment.

Another form of ROI measurement strategy is to determine required freight rates (RFR) for the ship design proposed for service. Minimizing the RFR also can form the basis for design optimization studies.

Naval ships do not have a bottom line commercial profit consideration. These ships are put into service only to satisfy a national security commitment to its citizens. However, as limited government funds address an ever-widening array of government responsibilities, naval ships designs now must be developed with an increasing focus on getting *the biggest bang for the buck.* Design and engineering tradeoff studies can minimize costs without sacrificing mission capabilities. The objective for these studies is an increase in mission capabilities without an increase in cost.

10.5 ORGANIZING THE COST ESTIMATE

Normally, the bid estimate must be organized according **to** a Work Breakdown Structure (WBS) defined within the request for proposal from the shipowner. For Navy bids, estimates typically must be provided according to the Navy's Ship Work Breakdown Structure (SWBS), a breakdown of work and material by ship system categories. Commercial shipowners provide more latitude, but usually they too want to review the estimate to some practical summary levels of detail that identifies the basic ship components and systems, especially if there are various design options to be considered.

But the estimate also needs to reflect the impact that the proposed shipyard's build strategy has upon the pricing information. The concept of modular construction points the way for a need for modular cost estimating. The *Product-oriented Work Breakdown Structure* (PWBS) (5) is another view of the work by ship systems (SWBS), but it also allows costs to be packaged in terms of the modular construction environment. An estimating approach that is organized around both a systems-based WBS and the modular construction concept allows different build strategies to be explored and the consequences these issues have upon the bid proposal pricing.

10.5.1 Formats of Cost Estimate

The cost estimate must identify all direct costs (labor, material and subcontracted services) within the proposed scope of work. Direct costs should include technical, production and all supporting shipyard services that are not considered indirect by the shipyard (supervision, temporary ship services, quality control, planning, project management, etc.). Where applicable, miscellaneous expenses such as freight and transportation, insurance fees and taxes and duties attributable to direct costs also need to be considered. Separated from direct costs, indirect costs for overhead, material mark-ups, and general administrative efforts are necessary to complete the cost estimate.

The estimate needs to be developed within a framework that summarizes the costs within prescribed categories that can be monitored as the estimate evolves. The shipyard typically has its own work breakdown structure that is the basis for the company's operating systems that collect and manage return costs. These return costs provide the historical basis for many of the cost estimating relationships (CERs) used by the cost estimator.

The WBS is a means for summarizing the scope of work and should provide the format for identifying and cataloging the details of the cost estimate:

- manufacturing and assembly operations that can be easily identified by task (discrete work production work orders),
- production support activities (level of effort work such as shipyard services),
- technical services (design and engineering),
- subcontracted services, and
- material and equipment.

For new construction, the WBS defines the ship and its systems as designed for the owner:

- hull structure,
- propulsion plant,
- major equipment items,
- distributed Systems (Electrical, Piping, HVAC), and
- cleaning and paint.

The additional efforts, including design and engineering services and shipyard support efforts, must also be identified and incorporated into the work breakdown structure for the estimate:

- shipyard services, and
- technical services.

It is also sometimes required, especially for government projects, that the cost estimate be provided to the prospective customer (the shipowner) according to a work breakdown structure of the owner's choice. Therefore, an estimating approach that supports multiple work breakdown structures can save a lot of time from the estimator's point of view.

The following describe the more prevalent WBS configurations in use today:

10.5.2 Ship Work Breakdown Structure (SWBS)

The U.S. Navy's SWBS is the most familiar of the systems-based work breakdown structures. However, when systems-based structures were the standard for managing ship construction, every shipyard devised their own variation to suit their own needs and preferences. Today, ship design still largely follows a SWBS format, particularly for weight control and for systems design. The transition to product and process-based formats is not typically made until detail design is underway.

10.5.3 Product-oriented Work Breakdown Structure (PWBS)

Once any complex product such as a ship has been designed, planning and engineering efforts need to be applied toward maximizing production efficiencies. This effort entails organizing work and resources that promote productivity and minimize non-value added costs. The concept of group technology, for example, supports this objective and enables engineered ship systems to be broken down into definable interim products. These products can exploit significant cost and schedule savings because they enable the work to be performed under more convenient and more easily performed work conditions.

Figure 10.1 illustrates a PWBS that identifies the basic areas of the ship (zones) and a progression of structural blocks assemblies, and outfit units that ultimately constitute the total ship product. It also shows where the PWBS elements change from a process focus to a product focus. The U.S. Navy's PODAC program has developed a generic PWBS, and a user-training program on its formulation is available over the Internet (6).

10.5.4 Shipyard Chart of Accounts (COA)

Each shipyard has its own internal work breakdown structure used to plan and manage its costs. The COA traditionally had been systems-oriented, although every yard had its own flavor and preference for identifying and categorizing ship systems. Over the years, shipyards have been replacing their systems-based work breakdown structures with formats that are more product and process-oriented.

The importance of the COA to the cost engineer is that the COA is the basis with which the shipyard collects costs and with which the shipyard measures the cost performance of its work.

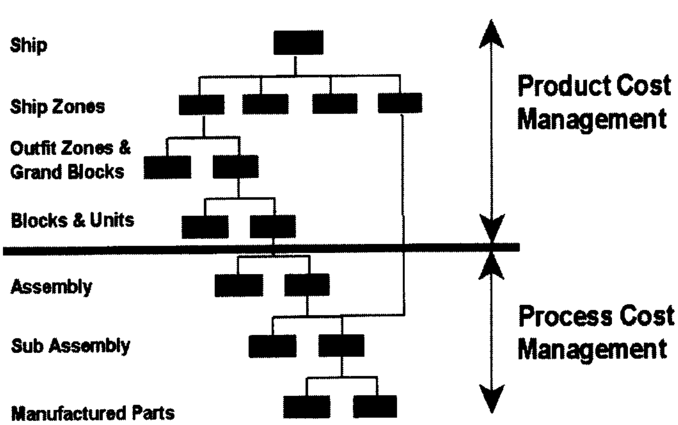

Figure 10.1 Product/Process Configuration & Cost Management

10.6 COST ESTIMATING RELATIONSHIPS

Cost Estimating Relationships (CERs) provide the qasic means for estimating costs. CERs come in many different flavors and varieties. They allow cost estimates to be developed for various material products, parts and components and labor processes including support services.

CERs come in many different levels of detail (Figure 10.2). Costs can be estimated at very high levels during concept stages of design or they can be estimated at very low levels from detail bills of material. In between these levels there are CERs that provide perhaps more accuracy possible from available design information but without the precision of what might be obtained after detail design and engineering has been completed.

A Cost Estimate Relationship (CER) is a formula relating the cost of an item to the item's physical or functional characteristics or relating the item's cost to the cost of another item or group of items. Examples:

- labor for steel block assembly at 25 man-hours/tonne,
- material cost for pipe at $25/meter; and
- labor for shipyard support service at 10% production hours.

CERs are typically developed directly from a measurement of a single physical attribute (quantity and unit of measure) for a given shipbuilding activity, and the cost of performing the activity. If the shipyard uses the same attribute for the same activities for each ship it builds, it can compile a database of cost-per-unit of measure for each of

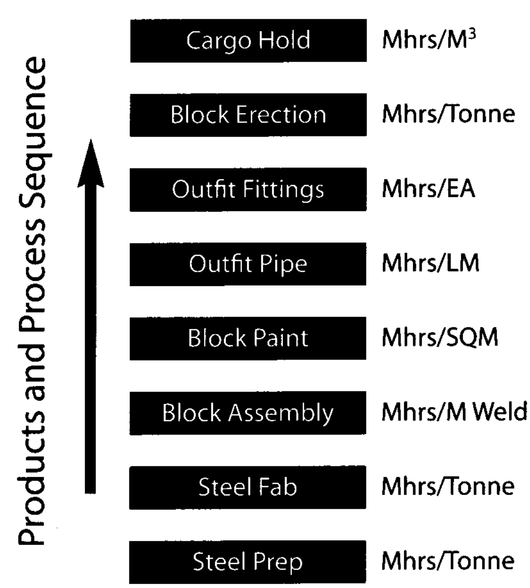

Figure 10.2 Possible Levels of Cost estimating Relationships

its different activities. Some CERs may be developed for a number of physical attributes. CERs may be developed to determine a variety of costs and cost-related parameters, including labor hours, material costs, overhead, weight, numbers of items, etc.

While most CERs are simple linear relationships. For example, 10 man-hours per pipe straight spool, others can be more complex formulations. High-level CERs, for example, more often exhibit non-linear relationships to accommodate the costs across a wide range of applications and variety of detail requirements, for example, Steel Cost = O.OO255~o.99.

Generally, five types of CERs are used and are defined separately, which will be described in the following subsections.

10.6.1 Manual CERS

Manual CERs are determined from external information such as vendor or subcontractor quotations.

10.6.2 Calculated CERS

Calculated CERs are determined from a single ship set of return cost data based on an actual cost expenditure and its associated measurable parameter, for example, labor hours per square feet of painted area.

10.6.3 Predictive CERs

Predictive CERs are developed from return costs from multiple ship sets or from costs collected from a given manufacturing process where costs exhibit a pattern of change over time. The predictive CER is the trend value of unit cost expected to apply for the given contract application.

10.6.4 Empirical CERs

Empirical CERs are developed by collecting a number of physical attributes (parameters) for a shipbuilding activity, such as ship type and size, part weight, part area, part perimeter, joint weld length, number of processes applied, number of parts involved, etc., as well as the cost of performing the activity. If this data is collected for a number of ships, in the same shipyard, a statistical analysis may determine the statistical *significance* of the parameters and the equations with coefficients and exponent values for the activity CER. The equation coefficients and exponent values are shipyard-dependent and will reflect its level of productivity for the activity. If facility parameters are included, the impact of facilities on productivity will also be evident.

10.6.5 Standard Interim Products CERs

An interim product is any output of a production work stage that can be considered complete in and of iteself. It also can be presented as an element within any level of a product work breakdown structure (PWBS).

As shipyards adopt standard interim products as the primary basis for building ships, the interim products themselves can form the means for developing high-quality cost estimates.

The interim product *cost estimate package* consists of a set of cost items and/or cost item CERs each describing labor and/or material costs. The labor costs may be broken down into the product's sequence of manufacturing and assembly stages. They may also include indirect cost efforts such as supervision and material handling, as well as related direct costs such as testing.

The interim products can be defined at any level of the PWBS. The higher the level, the more ship type-specific they are likely to be. These interim products become, in effect, high level complex CERs because they may include any number of cost items and these cost items may be parametric to any number of different defining characteristics.

The use of the standard interim product as a vehicle for cost estimating is sometimes referred to as a *Re-use* package that can operate with a variety of applications. The important aspect of the package used repeatedly as needed in developing a project cost estimate.

At issue for the estimator is what kind of CER is appropriate at any given stage of the design process. Detail CERs are of little value when few details are known. Similarly, high-level CERs are not acceptable when their assumptions no longer fit the problem at hand. Furthermore, the CER must identify the cost driver for the scope of work being estimated. The cost driver is a controllable ship design characteristic or manufacturing process that has a predominate effect on cost.

Finally, the real problem becomes this: where does one obtain the data necessary to develop realistic and appropriate CERs that can be meaningfully applied at any given time during the design evolution process?

10.7 USE OF HISTORICAL COSTS

A cost estimate is only as good as the information supporting the estimate. For shipyards, historical cost information is invaluable for developing cost estimates for new work. However, historical information needs to be both accurate and collected in ways meaningful to the estimating process. For example, if historical costs cannot be collected in ways that identify modular block costs, estimating by modular blocks can be difficult and will probably have a relatively high degree of risk in the accuracy and validity of the estimate.

It is very important that the shipyard have in place a cost planning and data collection system that is capable of organizing costs in ways that can directly benefit the estimating process.

10.7.1 Cost Collection Methods

Shipyards collect costs in the following manner: labor costs (labor hours) are collected from time charges to production work orders. Material costs are collected from purchase orders and from stock transactions when applicable. Shipyard work orders generally are organized around work type and stage of construction, while material often is cataloged (requisitioned) by ship system. The correlation of material to work orders can be obtained from issues of material to work orders or the requisitioning of bills of material to the PWBS.

From a cost collection perspective needed for cost estimating, the work orders should identify *scope* or the physical. That is, material throughput quantity for which the work is being done. For example, a work order may prescribe a budget of *x-hours* to assemble *y* material items, generally of size *z*.

The labor hours and material costs then can be summarized up through the PWBS. The units of measure at any given level of the PWBS will be the most meaningful unit of measure. That is, the cost driver for that level. For example, the unit of measure for steel fabrication might be based upon the number of parts, while ultimately the unit of measure for block erection would be best described by a weight or joint weld length unit of measure.

Even though high-level CERs by ship systems are needed for concept and preliminary design estimating, modem ship production methods no longer allow costs to be collected directly by ship systems. The production management software systems implemented at many shipyards can develop CERs only by measuring actual costs against known work order throughput parameters (meter of weld, square meter of plate, number of pipe spools, etc.). Many of these shipyard systems have little means to transform these product- and process-oriented CERs into the desired high level, ship systems and mission oriented CERs.

10.7.2 Transforming PWBS Costs to SWBS Costs

Complex products, such as ships, are normally designed system by engineered system. However, manufacturing does not maximize its cost efficiency and schedule performance if the work is planned and executed system by system.

Group technology and zone sequence scheduling are examples of executing work by interim product (units, blocks and modules) and by stage (fabrication, assembly and erection). These examples of work objectives transfoIin SWBS into a parallel PWBS. This transformation occurs when the systems-oriented ship design information is processed for necessary work instructions by production engineering.

In order to provide production cost data that is SWBS-oriented, some reverse transformation is required. Some shipyard production management systems have the capability to transform product- and process-oriented work orders so that ship systems costs can be collected. Methods have been devised for allocating or distributing costs that are effective, although somewhat approximate. One approach is to allocate costs based upon a planned breakdown of budget by ship systems involved in the work order. Then, when time charges are entered, they are distributed automatically on a pro rated budget basis back to the applicable ship systems. Typically, such work orders are restricted to a single type work process, such as fabricating pipe spools across ship systems. Therefore, the allocation can be a fair and reasonable representation of the actual work performed on each system.

Another approach is for the estimator to analyze and compile detailed production data and correlate these costs to some functional characteristic of the ship. For example, the electrical costs can be summarized and related to shipwide electrical load, such as kW. Such a CER may be directly useful for estimating at concept and preliminary stages of design.

A third approach is to develop systems-based CERs from shipyard work standards applied to the ship system's bill of material.

10.8 IMPACT OF BUILD STRATEGY

Cost estimates should directly reflect the shipyard's relative level of productivity. The shipyard that desires to maintain its competitive advantage by reducing costs and contract schedules must find areas where savings can be achieved. Savings can be significant and can come from a variety of sources.

The methods used to organize and execute work within the shipyard can affect work performance and this impacts costs to a very significant degree. One rule of thumb says that for every hour required to assemble material in the shop, it takes 3 hours to do it on-block and 5 hours to do it onboard. While this is an overly simplistic assessment, it does indicate that there are more optimum times during construction when work can be undertaken more productively. Another impact is the use of alternative manufacturing processes, including the use of out-sourced services.

10.8.1 Modular Construction Methods

In the past, shipyards used to build ships ship system by ship system. The collecting of costs by ship system was a relatively straightforward procedure. However, better methods for more productive organization of work have come into play. The packaging of work now focuses not on the specific ship systems, but upon the nature of the work to be performed. The objective is to do the work when the working conditions are most productive and to eliminate or minimize any efforts that do not add value to the activity. This means that work done in shops are typically more productive than if the work were scheduled for on board. To complement this concept, modular construction techniques, including on block construction (Figure 10.3) and advanced outfitting have become the preferred methods for maximizing production efficiencies. These methods, however, do require more advanced product engineering in order to gain the full potential of efficiencies and cost savings. What was once a ship systems-oriented way of organizing work and collecting costs has now given way to organizing work and collecting costs by interim products (sub-assemblies, assemblies, hull blocks, ship zones) and manufacturing processes (cutting, welding, assembling, etc.). As described earlier, the interim products can be standardized and identified within a PWBS.

10.8.2 Group Technology Manufacturing

Significant cost savings are possible with the application of group technology to product development and production processes. Group Technology is a method for grouping like or similar work together in order to gain the benefits possible from batch manufacturing, including elimination of

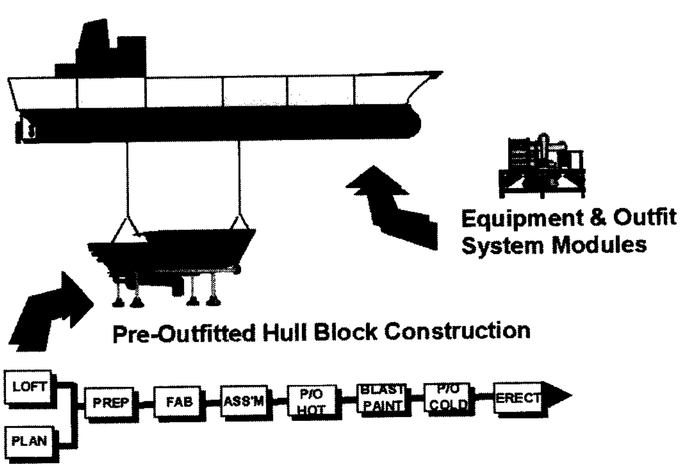

Figure 10.3 Advanced Outfitted hull Block Construction

multiple set-up process steps, etc. Group Technology can be applied to many different kinds of work. The more classical example is the fabrication of a large group of same-size pipe spools. However, the conceptevokes similar time and cost savings with zone sequencing of trade work (scheduling a given trade to work uninterrupted and unencumbered in specified ship spaces or zones or on a specific structural block's advanced outfitting). Structural panels and sub-assemblies also can be scheduled in ways to maximize the productivity objectives of Group Technology.

However, from a material management logistical and handling cost point of view, the group technology approach should not be an absolute objective and not necessarily employed across the entire ship's structure in one single manufacturing run (assuming drawings and material are all available at this time). World-class shipyards often manufacture parts and sub-assemblies in separate batches corresponding generally to hull block requirements and their production assembly schedules. This limited application of group technology also can be seen with deliveries of outsourced manufactured parts, since the shipyards require delivery of these items in batches corresponding to the schedules of the hull block construction program.

10.8.3 Performance Measurement Systems

In order to identify what changes will provide the most significant levels of benefit, a shipyard must be able to evaluate its operations in quantitative terms. This means that the shipyard must have implemented a reasonably accurate means for measuring cost and schedule performance at appropriate levels of detail. Performance measurement systems should provide the visibility of performance that will indicate whether or not changes are warranted and ultimately if the changes are proving to be effective. Return cost information from such systems form the information needed to develop high quality predictive CERs that reflect not only past cost performance, but also anticipated performance on new work.

10.9 COST ADJUSTMENTS AND FORECASTS

CERs are based not only upon the type of material being fabricated or assembled, but also upon a prescribed set of shipyard performance characteristics. These characteristics may include the specific shipyard facilities, tools and equipment employed; the productivity and skill levels of the workers; the producibility of the design; the approach to organizing the work, etc. These characteristics for each shipyard will vary, and the expected costs to perform these activities will vary accordingly.

The following sub-sections discusses various methods by which the estimator can make adjustments to CERs in order to refine a cost estimate with more accuracy to suit the given estimating circumstances.

10.9.1 Major Types of Cost Adjustments

The estimator can obtain CERs from any number of different sources, including CERs developed from actual shipyard return costs as well as generic CERs that may be available outside the shipyard. The cataloged CERs immediately available to the estimator may not always accurately reflect the expected costs for the application being estimated. Therefore, the estimator can either modify the cataloged CER or define with the existing CER an appropriate adjustment factor to apply when computing costs. The latter approach may be desirable if:

- The estimator wishes to preserve the original CER for control purposes, and/or
- The estimator wishes to perform a trade-off study to test the impact of a revised CER.

The following is an example of applying an adjustment factor to an existing cataloged CER:

$$CER_{adjusted} = F_{WCadj} \times CER_{catalog}$$

where F_{CERadj} is the shipyard's CER adjustment factor and $CER_{catalog}$ is the existing cataloged CER.

The estimator needs to take into consideration CERs for the effects of the shipyard's anticipated cost performance characteristics. These adjustments fall into the following categories:

- cataloged CER adjustments,
- work center productivity adjustments,
- stage of construction productivity adjustments,
- PWBS complexity adjustments,
- economic Escalation adjustments,
- learning Experience adjustments,
- high volume business material savings, and
- Material Waste adjustments.

Example: An industry generic CER might be 12 labor hours per tonne to assemble flat steel panel sections, such as, deck assemblies. This production rate is based upon a facility using largely manual welding of stiffeners to the plate. The shipyard, however, might have an automated panel line where productivity is improved by a margin of 75%. Therefore, the CER adjustment factor for the shipyard would be 0.25 (100%-75%). When the factor is applied, the adjusted CER for the shipyard computes to be 3.0 labor hours per ton.

How is the adjustment factor determined? Usually, the estimator can make a comparison between the cataloged CER and comparable historical data from the shipyard or other sources known to be accurate. If there are cataloged CERs that are for similar work (for example, CERs for different size pipe) and they belong to a relatively consistent series of cost data, oftentimes the same adjustment factor can be used for all of them.

10.9.2 Work Center Productivity Factor

The estimator may wish to review the effects of changes in the way the shipyard might want to execute the work. Then the estimator may use another adjustment factor that reflects certain gains or losses in productivity within specified shipyard work activities, such as, work centers, and evaluate the changes in the project's total estimated costs. Doing this through an estimating process can provide valuable insight into a possible positive a return on investment.

Example: If the cataloged CER identifies 2 man-hours per ton to paint a hull block, including extensive scaffolding costs, the shipyard that employs mobile lift wagons may be able to reduce the cost by 50%. Therefore, a productivity factor of 0.50 can be used to adjust the cataloged CER.

$$CER_{adjusted} = F_{WCadj} \times CER_{catalog}$$

where F_{WCadj} is the shipyard's productivity factor for the painting operation and $CER_{catalog}$ is the existing cataloged CER.

It is important to note that when a specific shipyard's performance factor has been defined for a specific work process, it should be applied to *all* cataloged CERs that are used to develop cost item estimates for work in that center.

Additional information can be obtained on the relative increases in productivity that can be expected by implementing changes (modern process equipment) in the shipyard facilities and operating practices.

10.9.3 Stage of Construction Productivity Factor

Generally speaking, the earlier stages of construction provide reduced cost opportunities to perform work, especially for material installations.

The best working environment exists usually within workshops. Here, tools and equipment and other support facilities are nearby, material is readily available without undue handling costs, and the working conditions are unaffected by weather and location.

In addition, work performed within workshops means that work is done only on relatively small components of the ship. Little effort is required to get access to these components and little time is lost moving men, equipment and material to the work site.

On Board Work is the least productive working area. Here more time is required to access the work, to provide workers, material, tools, and equipment and support services. Adverse climatic conditions also may have a negative impact upon costs.

On Block Work typically represents an opportunity to perform work more conveniently and more productively **than** on board. The hull block is small relative to the entire ship's structure, so accessing it to install various outfit items is relatively easy (Figure *IOA).* The work sites for outfitting hull blocks are usually nearby workshops. Hence, the cost to supply material, workers, tools and equipment is much lower than what is needed to support comparable work on board. If hull block construction can be done under cover, added costs from weather-related problems can be essentially eliminated.

On-Unit Work involves the assembly of outfit material into various forms of outfit units, pre-plumbed pumps and machinery, equipment consoles, pipe racks, furniture modules, etc. (Figure 10.5). Outfit units tend to be relatively small and can be done in workshops. Therefore, they can be assembled under the most favorable and productive working conditions. Since outfit units can be installed either on block or on board, there are cost savings if installed on block.

Work Orientation also affects costs, whether done on unit, on block or on board. Down-hand welding and assembly is much easier and far more productive than overhead work (Figure 10.6). If over-head work requires staging, costs for these operations can increase significantly.

Stage of construction productivity factors may be developed using one of the stages of construction as the baseline for the costs. The stage of construction productivity factors must be included in the work center productivity factor described above. The cost differentials due to stage of construction become critically important as shipyards try to implement changes in the way they do business and improve their competitive position in the market place. The build strategy elected by the shipyard will determine how much of the work can be done at the earlier, more productive stages of construction.

10.9.4 Design Complexity/Density Factor

The stage of construction productivity factor helps determine cost differentials for work done at different stages of the construction cycle (in shop versus on block versus on board). However, an additional factor needs to be introduced for adjusting construction cost estimates for an increase or decrease in the relative complexities of the ship design or interim shipbuilding products. For example, on

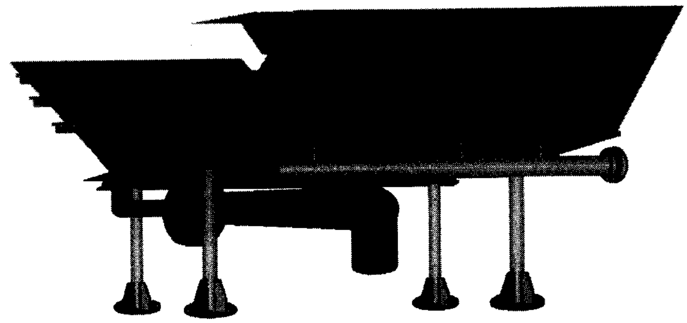

Figure 10.4 On Block Outfit

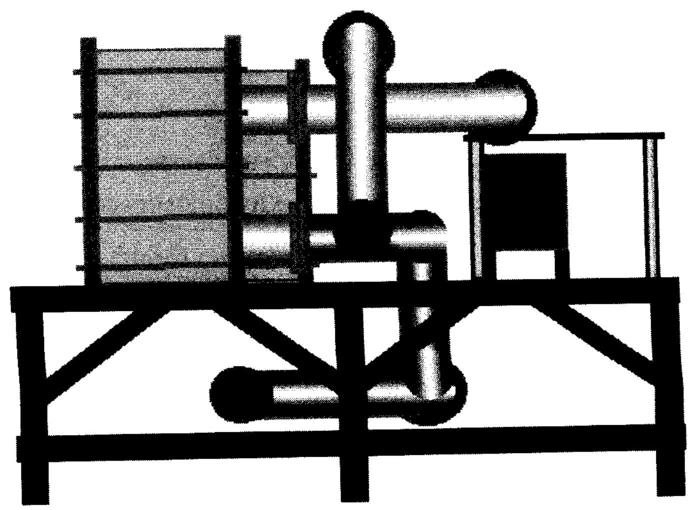

Figure 10.5 On Unit Outfit

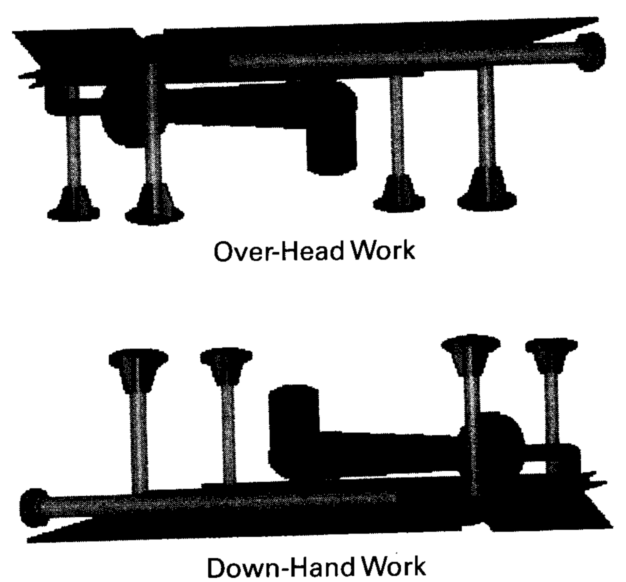

Figure 10.6 Examples of More Productive Down Hand Work Orientation

board work may generally require five times more labor hours than equivalent work done in the shop. But, if the ship zone is particularly crowded (denser), the work area may be much more difficult to access. The costs therefore may require even more labor hours to complete the work.

Table 10.1, exhibits typical added cost margins used by ship repair estimators to account for added difficulties for where the work is performed on board ship. Similar problems exist in new construction where the working conditions vary from ship zone to ship zone, hull block by hull block. The complexity factor should be sensitive to the level of the PWBS hierarchy. For example, the manufacturing of parts for a particular ship zone may not be affected by the complexity of the zone, but the installation of those parts in the zone may be very much affected by the complexity or confinement of the space on board.

10.9.5 Economic Inflation Adjustment Factor

The estimator applies the complexity adjustments in the following manner:

$$CER_{adjusted} = F_{PWBSadj} \times CER_{catalog}$$

where $F_{PWBSadj}$ is the complexity factor and $CER_{catalog}$ is the CER cataloged on the system database. Costs are influenced not only by various performance factors within the shipyard, but also by factors outside the shipyard. Costs can be influenced by inflation/deflation and these effects change over time.

Various economic forces in the marketplace create pressures upon costs to either increase or decrease them over time. In a free market economy, increased costs are caused by *inflation* and usually occur when demand outstrips supply. Decreased costs are caused by the reverse, called *deflation,* and are caused by supply being greater than demand. Similar changes in costs can occur with changes in manufacturing processes, engineering technologies, etc.

For cost estimating purposes, costs relevant during one period of time can be used as costs relevant to another period in time. However, these costs need to be adjusted to reflect the economic conditions of that other period of time. This process of adjusting costs from one period to another is called *cost escalating.* Although the term escalating normally infers an increasing of cost, a similar process of adjustments applies to costs that decrease over time.

To escalate costs, the following elements of information are required:

- the original time and cost known to apply at that original time, and
- the anticipated time and change in cost from the original time to the anticipated time.

TABLE 10.1 Typical Added Complexity Of Ship Zone Work

Ship Zone	*Added Cost Factor*
On Weather Deck	0%
Oil Tanks	25%
Engine Room	50%
Superstructure	25%
Pump Room	50%
Holds	10%
Double bottom	25%

The increase or decrease change in cost is usually treated as a general percentage. For example, if inflation has increased by 3.5%, then on average, goods and services have increased in cost by the same amount. Complete tables of these changes over a range of years are available from various sources (for example, the Bureau of Labor Statistics and the Naval Center of Cost Analysis). The Consumers Price Index, published annually by the Government, compiles these percentages into an *index* so that costs from one year to any other year in the table can be adjusted (that is, escalated). These indexes are produced on a monthly basis and are available over the Internet. Table 10.11provides an example.

Most escalation indexes are provided as historically tracked. Index tables will vary from source to source depending upon what is the basis for its valuation and what is the base year costs being used to compare other year costs in the table. In order to perform cost escalations for years beyond available index tables, the estimator can extend these indexes with estimates of what these indexes might be in the future.

These indexes allow any CERs to be adjusted for inflation/deflation. CERs from different periods of time can be individually adjusted so that they *all* are applicable to the same year, that is, base year, for which an estimate is being developed.

The estimator is cautioned against escalating costs more than several years or across periods where costs changes are significant. The indexes are provided only on an averaging basis and may not accurately reflect changes in costs for the specific cost item at hand.

To use escalation index tables, the following definitions are required:

- the known cost is called the *cataloged coso*
- the time period of the known cost is called the *cataloged cost year*. Typically, cost estimate data is comprised of known costs collected over a range of years. The esca-

TABLE 10.11 Sample Escalation Index Table

Year	*Index*
1995	1.12710
1996	1.1616
1997	1.1964
1998	1.2323
1999	1.2693
2000	1.3074
2001	1.3466

lation process must adjust these costs so that they all can apply to some common (baseline) period of time,

- the cost index recorded for the *cataloged cost year* is called the *cataloged cost year index,*
- the time period whereby all costs are to be developed for an estimate is called the *base year* for the estimate. The *base year* typically is the current year. Costs cataloged at years earlier than the *base year* need to be updated. One method for updating is to obtain new cost information applicable to this *base year.* Another method is to adjust earlier costs using escalation index tables so that these costs apply to the *base year,*
- the cost index recorded for the *base year* is called the *base year index.* The process of escalating the cost from its *cataloged cost year* to the *base year* is:

Base Year Cost = *(base year index/cataloged cost year index)* x *cataloged cost*

- the time period projected in the future for the cost estimate is called the *projected cost year. Projected costs* are the *base year* costs advanced to some designated year in the future. These costs normally are advanced using the escalation tables, although some large equipment cost items may have projected costs quoted and guaranteed by vendors, and
- the cost index recorded for the *projected cost year* is called the *projected cost year index.* The process of escalating the cost from the *base year* to the *projected year* is:

Projected year cost = *(projected year indexlbase year index)* x *base year cost*

Example: If the last price quotation for life saving devices was in 1997, then the CER that defines that cost must be cataloged with the year of 1997. The CER escalation adjustment factor can be computed in the following manner:

$$F_{escalation} = Index_{base\ year} / Index_{cost\ year}$$

where $Index_{base\ year}$ is the escalation index for the year corresponding to the year in which the project is planned to expend the cost item; $Index_{cost\ year}$ is the escalation index corresponding to the year in which the CER costs have been recorded on the database.

With this escalation factor, the cataloged CER can be escalated for the base year:

$$CER_{adjusted} = F_{inflation} \times CER_{catalog,}$$

For the life saving devices example, the 1997 costs can be escalated, using data presented in the above table to the year 2000 as follows: Find the index values for the base year (1997), and for the projected year (2000).

$$\begin{aligned} Index_{cost\ year} &= Index_{1997} \\ &= 1.1964 \\ Index_{base\ year} &= Index_{2000} \\ &= 1.3074 \end{aligned}$$

The escalation factor that adjusts the 1997 cost to the 2000 cost is a simple ratio as follows:

$$\begin{aligned} F_{escalation} &= Index_{base\ year} / Index_{cost\ year} \\ &= 1.3074 / 1.1964 \\ &= 1.093 \end{aligned}$$

Escalation factors less than 1.0 indicate economic deflation. Factors greater than 1.0 indicate inflation. Therefore, in the year 2000, the life saving devices is estimated to cost 1.093 times the cost in 1997.

If the projected project year is different than the current calendar year (base year), retrieve the cost items and replace their Base Year with the projected project year. If a project has costs cataloged for different projected years, this process will have to be done in yearly stages.

10.9.6 Composite Performance Factor

From the above discussions, the estimator may use a variety of cost adjusting factors. A composite adjustment factor is simply a straight multiplication of individual adjustment factors:

$$CER_{adjusted} = F_{inflation} \times F_{CERadj} \times F_{WCadj} \times F_{SOCadj} \times F_{PWBSadj} \times CER_{catalog}$$

10.9.7 Learning Experience Adjustment Factor

The cataloged CERs usually establish costs under a certain prescribed set of production circumstances. Traditionally, the CER relates to costs for a prototype or the first of a series construction program. It is often, but not universally accepted that multiple products benefit from a *learning curve* (7). That is, it is anticipated that for a series of ships each ship labor cost should decrease from continued improvements introduced over time in the build strategy and manufacturing processes and refinements in production engineering.

Therefore, when the estimator has developed the cost estimate for the lead ship of the series and copies this estimate for each of the follow ships, the learning curve factors (Figure 10.7) can be applied to each of the follow ship estimates. The theory behind learning curves is that the percentage improvement is constant and occurs every time product quantity is doubled. That is 2, 4, 8, 16, etc. It has been found to apply more to products that are produced in large quantities (lOOs) and in relatively short times (hours).

While production costs can decrease as from ship to ship, some shipyards often experience an increase in engineering costs for the second ship. This is recognition that the prototype engineering was less successful and that a second-wind effort is needed to get the series program on a more efficient footing.

While the above learning curves indicate a gradual cost reduction per ship of the series, examining cost reductions for standard interim products and manufacturing processes across all ship types can realize the same experience. As shipyards introduce standard interim products as the primary means for designing and building ships, learning becomes a less important consideration. This is a good indication that

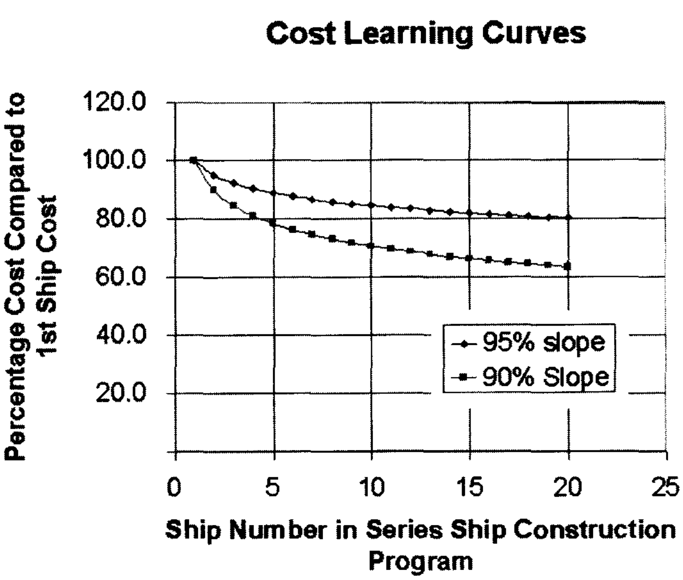

Figure 10.7 Typical Learning Curve Factors

the cost reductions are gained not by an actual learning experience, but more by a diminishing of expensive rework that should not have occurred in the first place.

10.9.10 Multi-Ship Material Cost Advantages

Besides the benefits of learning curve effects upon labor costs, multiple ship contracts also can have a positive effect upon material costs. It has been estimated that the promise of a larger order backlog can elicit as much as a 15-20% cost reductions from vendors and suppliers. Busy shipyards often can gain lower material costs simply because their suppliers can rely upon these shipyards with long-term business opportunities.

10.9.9 Multi-ship Engineering and Planning Advantages

Obviously, for multi-ship contracts the engineering and planning only need to be prepared once, and the cost (nonrecurring) can be spread over each ship in the series. However, there is still a relatively small engineering and planning cost (recurring) for each ship and it must be included for the follow-on ships.

10.9.10 Material Waste Factor

What material is required from an engineering point of view should be reconsidered from a procurement point of view. Production often cannot consume 100% of the purchased material without some measure of waste. Therefore, the estimator needs to account for waste in estimating the cost of material in the following manner:

$$\text{Total Cost}_{\text{material}} = \text{Quantity} \times (1.0 + F_{\text{waste}}) \times \text{CER}_{\text{material}}$$

where F_{waste} is the estimated waste factor and $\text{CER}_{\text{material}}$ is the material cost CER.

10.10 COST RISK

When bidding on new contracts, shipyards look at production cost and schedule risk. To remain competitive, shipyards develop strategies to minimize their exposure without losing a good business opportunity. This means that the bid problem needs to be examined and understood to the best of one's ability to do so. The bid process requires this examination to focus not only on the shipyard's own internal performance abilities, but also that of the competition and that of the shipowner's ultimate objectives and funding resources.

Risk, or uncertainty, can be associated with any or all cost items included within a developing project cost estimate. The greater the cost risk, the less likely, or probably, that the cost estimate is realistic. The lower the risk, the greater is the probability that the cost estimate is valid.

Uncertainty can be expressed, or represented, as a distribution of cost estimates between certain values. Outside this range of expected values one would expect that other values would have very low probability (high risk). A number of different cost probability models are possible.

Two popular types of risk analysis methods include Monte Carlo Cost Risk and PERT (Project Evaluation Review Technique) Cost Risk. Both the methods summarize expected costs and levels of cost confidence at the project level of the work breakdown structure with little additional information required from the estimator.

The risk can be applied at different levels and thus different approaches. For example it can be applied to a completed estimate. In this case the risk will either be based on historical performance of the shipyard against it's estimates and used to determine the bid price to give a confidence level of 100% that it would achieve its profit goal. It could also be based on a predicted distribution of competitors bid prices and then used to determine a bid price for the shipyard that would give them sayan 100% confidence level of winning the bid.

It also could be applied at each item level in the estimate with actual equipment quotations allocated a probability of I, whereas estimated quantities for both material and labor being assigned a probability distribution based on estimators confidence in the estimate. The completed estimate would be a price distribution, from which the shipyard could choose the price it would bid.

Figure 10.8 illustrates a *normal* probability of cost distribution. The particular characteristic of this type of distribution is that there is an average or mean cost value that has the greatest probability of occurrence. Above and below this

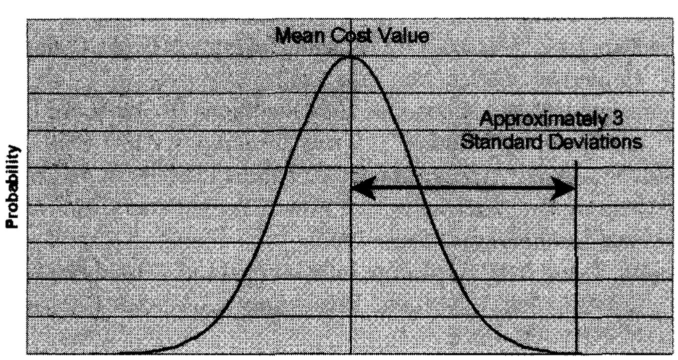

Figure 10.8 Normal Probability of Cost Distribution

mean cost value, the cost probabilities become less and less and the distribution of these probabilities is symmetrical about the mean. This model has characteristics similar to that of the triangular distribution model, but obviously requires a good deal more information about the relationship between probability of occurrence and actual cost values.

This is not typically possible or practical for the estimator to determine. However, most cost risk analyses use approximate methods in order to provide a reasonable indication of just how risky a particular cost estimate is likely to be.

In order to achieve maximum benefit, there needs to be a risk management strategy. It starts with collecting and analyzing known facts about the problem. This is called *disaggregating* the risk. The process involves breaking down a large and unwieldy risk problem into smaller, more manageable pieces.

As the problem is broken down, the various elements of the problem can be risk-minimized by applying to them what is called *familiarity advantages.* This is the application of core competencies to better understand each piece of the problem and minimize the risk of the unknown. In other words, when you know what you are doing, you are less likely to make a mistake than when you are trying something for the first time.

10.11 COST ESTIMATING SYSTEMS

There is a number of cost estimating systems available on the market. In addition to the ubiquitous spreadsheets, the systems prevalent in use for cost estimating Navy ships are the following:

Advanced Suiface Ship Evaluation Tool (ASSET) addresses all engineering disciplines required for total ship design. It is used for new ship design and conversion studies and produces Rough Order of Magnitude (ROM) design information for concept design and feasibility studies. ASSET has direct program links to the ACEIT cost estimating system.

Automated Cost Estimating Integrated Tools (ACEIT) is a joint Army/Air Force program support by the Navy. Primarily SWBS-based, it accommodates indirect costs, escalation adjustments and learning curves. The system produces time-phased life cycle costs

Unit Price Analysis (UPA) estimates time-phased nonrecurring and recurring costs, indirect, and cost of money. The system offers factors to adjust the SWBS-based CERs for specific design characteristics and producibility.

PRICE Systems offer a parametric approach to estimating costs. A variety of adjustment (calibration) factors and empirical productivity values may be applied to standard CERs.

The PRICE systems are primarily SWBS-based and include functions for estimating life cycle, post-construction costs.

Product-oriented Design and Construction (PODAC) Cost Model is a relational database application that has libraries of CERs and expanded cost item packages that can be quickly applied to a cost estimate. The system allows costs to be generated by various work breakdown structures including ship systems SWBS, by product and manufacturing process (PWBS) and by the shipyard's own internal chart of accounts (COA) as well as by contract line items (CLINs) and repair item or specification paragraph. The system uses escalation tables, learning curves, and a variety of cost adjustment factors to accommodate differences in process efficiency, design producibility, etc. The system provides a cost risk analysis. Shipyard return costs can be linked directly into the database. A statistical analysis capability enables the estimator to analyze a wide cross-section of labor and material cost data and develop new CERs at various levels of detail.

There also are ship design systems that have cost estimating capabilities. Design synthesis tools employ design and cost estimating algorithms for specific ship types. These systems are useful for developing concept-level ship design characteristics and measuring the impact on cost from trade off studies. Examples of synthesis tools include the PODAC system empirical cost models, the USCG buoy tender, offshore cutter and patrol boat models. Synthesis models also are available from the University of New Orleans for container ships and tankers.

While synthesis tools employ high-level, generalized design and costing algorithms, there are other ship design tools with cost estimating capabilities that operate at more detailed levels of analysis:

- *Parametric Flagship,* a system developed under a Maritech ASE project, links various ship design and naval architecture analysis systems directly with the PODAC cost model (8),
- Intergraph's multiple discipline GSCAD system also linked with the PODAC cost model, and
- as of the time ofthis writing (2001), the Navy's ASSET design tool is being linked to the PODAC Cost Model.

Work also has been done developing systems for simulation-based acquisition (SBA). These systems dynamically link applications of design, analysis and evaluation software and enable the designer to optimize a given product's performance, cost and deployment schedule. The goal for these systems is not only to provide quantitative design, cost and schedule responses to a range of design and construction alternatives, but probabilistic responses of the inherent risk.

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Chapter 11

Parametric Design

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11.1 NOMENCLATURE

AM	submerged hull section area amidships (m^2)
AP	after perpendicular, often at the center of the rudder post
Aw	area of design waterplane (m^2)
Ax	maximum submerged hull section area (m^2)
B	molded beam of the submerged hull (m)
BM_T	transverse metacenteric radius (m)
BM_L	longitudinal metacenteric radius (m)
C	coefficient in Posdunine's formula, equation 5; straight line course Stability Criterion
C	distance aft of FP where the hull begins its rise from the baseline to the stem (m)
C_B	block coefficient = VfLBT
C_{BO}	block coefficient to molded depth D
C_B'	block coefficient at 80% D
C_{OWT}	total deadweight coefficient = *DWTJIJ.*
C,	transverse waterplane inertia coefficient
C_{IL}	longitudinal waterplane inertia coefficient
C_M	midship coefficient = AM/BT
C_m	coefficient in non prime mover machinery weight equation, equation 42
Co	outfit weight coefficient = W ofLB
Cp	longitudinal prismatic coefficient = V/AxL
C_S	wetted surface coefficient = S/-v(VL)
C_V	volumetric coefficient = VfL3
Cvp	vertical prismatic coefficient = V/AwT
C_{wp}	waterplane coefficient = AwfLB
C_X	maximum transverse section coefficient = Ax/BT
D	molded depth (m)
Der	depth to overhead of engine room (m)
DWT_C	cargo deadweight (t)
DWT_T	total deadweight (t)
E	modified Lloyd's Equipment Numeral, equation 33
Fn	Froude number = V/-V(gL), nondimensional
FP	forward perpendicular, typically at the stem at the design waterline
FS	free surface margin as % KG
Fv	volumetric Froude number = V/-V(gVI/3)
g	acceleration of gravity (mls²); 9.81 mls²
GMT	transverse metacentric height (m)
GM_L	longitudinal metacentric height (m)
hdb	innerbottom height, depth of doublebottom (m)
hi	superstructure/deckhouse element i height (m)
K	constant in Alexander's equation, equation 14; constant in structural weight equation
circle K	traditional British coefficient = *2F_V-Vn*
KB	vertical center of buoyancy above baseline (m)
KG	vertical center of gravity above baseline (m)
f!i	length of superstructure/deckhouse element i(m)
f!i	component i fractional power loss in reduction gear
L	molded ship length, generally LWL or LBP
Lf	molded ship length (ft)
LBP	length between perpendiculars (m)
LCB	longitudinal center of buoyancy (m aft FP or %L, + fwd amidships)
LCF	longitudinal center of flotation (m aft FP or %L, +fwd amidships)
LCG	longitudinal center of gravity (m aft FP or %L, +fwd amidships)

LOA length overall (m)
LWL length on the design waterline (m)
MCR maximum continuous rating of main engine(s) (kW)
circle M traditional British coefficient = $L/\nabla^{1/3}$
M_D power design or acquisition margin
M_S power service margin
N_e main engine revolutions per minute (rpm)
P_B brake power (kW)
P_D delivered power (kW)
P_E effective power (kW)
P_S shaft power (kW)
r bilge radius (m)
R coefficient of correlation
$\hat{R}$ Bales' seakeeping rank estimator
RFR required freight rate ($/unit of cargo)
R_T total resistance (kN)
s shell and appendage allowance
S wetted surface of submerged hull (m^2)
SE standard error of the estimate
SFR specific fuel rate of main engine(s) (t/kWhr)
t thrust deduction or units in tonnes
T design molded draft (m)
T_{reqd} required thrust per propeller (kN)
V ship speed (m/s)= 0.5144 V_k
V_k ship speed (knots)
w average longitudinal wake fraction
$W_{C\&E}$ weight of crew and their effects (t)
W_{FL} weight of fuel oil (t)
W_{FW} weight of fresh water (t)
W_{LO} weight of lube oil (t)
W_{LS} Lightship weight (t)
W_M propulsion machinery weight (t)
W_{ME} weight of main engine(s) (t)
W_o outfit and hull engineering weight (t)
W_{PR} weight of provisions and stores (t)
W_{rem} weight of remainder of machinery weight (t)
W_S structural weight (t)
γ water weight density; 1.025 t/m^3 SW at 15°C; 1.000 t/m^3 FW at 15°C
δ% distance between hull structure LCG and LCB (%L, + aft)
Δ displacement at the design waterline (t)
η_b line bearing efficiency
η_c electric transmission/power conversion efficiency
η_g reduction gear efficiency
η_{gen} electric generator efficiency
η_h hull efficiency = $(1 - t)/(1 - w)$
η_m electric motor efficiency
η_o propeller open water efficiency
η_p propeller behind condition efficiency
η_r relative rotative efficiency
η_s stern tube bearing efficiency
η_t overall transmission efficiency; just η_g with gearing only
σ fraction of volume occupied by structure and distributive systems
∇ molded volume to the design waterline (m^3)
∇_T hull volume occupied by fuel, ballast, water, lube oil, etc. tankage (m^3)
∇_{LS} hull volume occupied by machinery and other Lightship items (m^3)
∇_U useful hull volume for cargo or payload (m^3)

11.2 PARAMETRIC SHIP DESCRIPTION

In the early stages of conceptual and preliminary design, it is necessary to develop a consistent definition of a candidate design in terms of just its dimensions and other descriptive parameters such as L, B, T, C_B, LCB, etc. This description can then be optimized with respect to some measure(s) of merit or subjected to various parametric trade-off studies to establish the basic definition of the design to be developed in more detail. Because more detailed design development involves significant time and effort, even when an integrated Simulation Based Design (SBD) environment is available, it is important to be able to reliably define and size the vessel at this parameter stage. This chapter will focus on the consistent parametric description of a vessel in early design and introduce methods for parametric model development and design optimization.

11.2.1 Analysis of Similar Vessels

The design of a new vessel typically begins with a careful analysis of the existing fleet to obtain general information on the type of vessel of interest. If a similar successful design exists, the design might proceed using this vessel as the *basis ship* and, thus, involve scaling its characteristics to account for changes intended in the new design. If a design is to be a new vessel within an existing class of vessels; for example, feeder container ships of 300 to 1000 TEU, the world fleet of recent similar vessels can be analyzed to establish useful initial estimates for ship dimensions and characteristics. If the vessel is a paradigm shift from previous designs, such as the stealth vessel *Sea Shadow* (see Chapter 46, Figure 46.17), dependence must be placed primarily on physics and first principles. Regardless, a design usually begins with a careful survey of existing designs to establish what can be learned and generalized from these designs.

For common classes of vessels, parametric models may already exist within the marine design literature. Examples include Watson and Gilfillan (1) for commercial ships; Eames and Drummond (2) for small military vessels; Nethercote and Schmitke (3) for SWATH vessels; Fung (4) for naval auxiliaries; Chou et al for Tension Leg Platforms (5); informal MARAD studies for fishing vessels (6), offshore supply vessels (7), and tug boats (8); etc. Integrated synthesis models may also exist for classes of vessels such as in the U.S. Navy's ASSET design program (9). Overall design process and vessel class studies also exist within the marine design literature, for example Evans (10), Benford (11,12), Miller (13), Lamb (14), Andrews (15), and Daidola and Griffin (16). Any design models from the literature are, however, always subject to obsolescence as transportation practices, regulatory requirements, and other factors evolve over time. Schneekluth and Bertram (17) and Watson (18) are excellent recent general texts on the preliminary ship design process.

This section presents thoughts on the overall approach to be taken for the initial sizing of a vessel and methods for parametric description of a vessel. Section 11.3 presents example approaches for the parametric weight and centers modeling. Section 11.4 presents example methods for the parametric estimation of the hydrodynamic performance of a candidate design. Section 11.5 presents methods useful in the analysis of data from similar vessels determined by the designer to be current and relevant to the design of interest. Rather than risk the use of models based upon obsolescent data, the preferred approach is for each designer to develop his or her own models from a database of vessels that are known to be current and relevant. Section 11.6 presents a brief introduction to optimization methods that can be applied to parametric vessel design models.

11.2.2 Overall Strategy-Paint-Based versus Set-Based Design

11.2.2.1 Point-based design

The traditional conceptualization of the initial ship design process has utilized the *design spiral* since first articulated by J. Harvey Evans in 1959 (10). This model emphasizes that the many design issues of resistance, weight, volume, stability, trim, etc. interact and these must be considered in sequence, in increasing detail in each pass around the spiral, until a single design which satisfies all constraints and balances all considerations is reached. This approach to conceptual design can be classed as a *point-based design* since it seeks to reach a single point in the design space. The result is a base design that can be developed further or used as the start point for various tradeoff studies. A disadvantage of this approach is that, while it produces a feasible design, it may not produce a global optimum in terms of the ship design measure of merit, such as the Required Freight Rate (RFR).

Other designers have advocated a discrete search approach by developing in parallel a number of early designs that span the design space for the principal variables, at least length (11,14,19). A design spiral may apply to each of these discrete designs. The RFR and other ship design criteria are often fairly flat near their optimum in the design space. Thus, the designer has the latitude to select the design that balances the factors that are modeled as well as the many other factors that are only implied at this early stage. Lamb (20) advocated a parameter bounding approach in which a number of designs spanning a cube in the (L, B, D) parameter space are analyzed for DWT_T and volumetric capacity.

11.2.2.2 Set-based design

The design and production of automobiles by Toyota is generally considered world-class and it is, thus, the subject of considerable study. The study of the Toyota production system led to the conceptualization of Lean Manufacturing (21). The Japanese Technology Management Program sponsored by the Air Force Office of Scientific Research at the University of Michigan has more recently studied the Toyota approach to automobile design (22). This process produces world-class designs in a significantly shorter time than required by other automobile manufacturers. The main features of this Toyota design process include:

- broad sets are defined for design parameters to allow concurrent design to begin,
- these sets are kept open much longer than typical to reveal tradeoff information, and
- the sets are gradually narrowed until a more global optimum is revealed and refined.

This design approach has been characterized by Ward as *set-based design* (22). It is in contrast to point-based design or the common systems engineering approach where critical interfaces are defined by precise specifications early in the design so that subsystem development can proceed concurrently. Often these interfaces must be defined, and thus constrained, long before the needed tradeoff information is available. This inevitably results in a suboptimal overall design. A simple example is the competition between an audio system and a heating system for volume under the dashboard of a car. Rather than specify in advance the envelope into which each vendor's design must fit, they can each design a range of options within broad sets so that the design team can see the differences in performance and cost that might result in tradeoffs in volume and shape between these two competing items.

The set-based design approach has a parallel in the *Method of Controlled Convergence* conceptual design approach advocated by Stuart Pugh (23) and the parameter bounding approach advocated by Lamb. These set-based approaches emphasize a *Policy of Least Commitment;* that is, keeping all options open as long as possible so that the best possible tradeoff information can be available at the time specific design decisions have to be made. Parsons et al (24) have introduced a hybrid human-computer agent approach that facilitates set-based conceptual ship design by an Integrated Product Team.

11.2.3 Overall Sizing Strategy

The strategy used in preliminary sizing will vary depending upon the nature of the vessel or project of interest. Every design must achieve its unique balance of weight carrying capability and available volume for payload. All vessels will satisfy Archimedes Principle; that is, weight must equal displacement:

$$\Delta = \gamma LBT\, C_B\,(1 + s) \qquad [1]$$

where the hull dimensions length L, beam B, and draft T are the molded dimensions of the submerged hull to the inside of the shell plating, 'Yis the weight density of water, C_B is the block coefficient, and s is the shell appendage allowance which adapts the molded volume to the actual volume by accounting for the volume of the shell plating and appendages (typically about 0.005 for large vessels). Thus, with dimensions in meters and weight density in t / m3, equation 1 yields the displacement in tonnes (t).

The hull size must also provide the useful hull volume ∇_U needed within the hull for cargo or payload:

$$\nabla_U = LBD\, C_{BD}(1 - \sigma) - \nabla_{LS} - \nabla_T \qquad [2]$$

where D is the molded depth, C_{BO} is the block coefficient to this full depth, and cr is an allowance for structure and distributive systems within the hull. When the upper deck has sheer and chamber and these contribute to the useful hull volume, an effective depth can be defined (18). Watson (18) also recommends estimating C_{BO} from the more readily available hull characteristics using:

$$C_{BD} = C_B + (1 - C_B)\,[(0.8D - T)/3T] \qquad [3]$$

Equation 2 is symbolic in that each specific design needs to adapt the equation for its specific volume accounting; here ∇_{LS} is the volume within the hull taken up by machinery and other Lightship items and ∇_T is the volume within the hull devoted to fuel, ballast, water, and other tankage.

If the vessel is *weight limited*, primarily dry bulk carriers today, the primary sizing is controlled by equation 1. The design sizing must be iterated until the displacement becomes equal to the total of the estimates of the weight the vessel must support. A typical design strategy would select L as the independent variable of primary importance, then select a compatible beam and draft, and select an appropriate block coefficient based upon the vessel length and speed (Froude number) to establish a candidate displacement. Guidance for the initial dimensions can be taken from regression analyses of a dataset of similar vessels as described in Section 11.5 below. Target transverse dimensions might be set by stowage requirements for unitized cargo; for example, a conventional cellular container ship using hatch covers might have beam and depth of about 22.2 m and 12.6 m, respectively, to accommodate a 7x5 container block within the holds. Parametric weight models can then be used to estimate the components of the total weight of the vessel and the process can be iterated until a balance is achieved. Depth is implicit in equation 1 and is, thus, set primarily by freeboard or discrete cargo considerations.

An initial target for the displacement can be estimated using the required total deadweight and a deadweight coefficient C_{OWT} = *DWT/il* obtained from similar vessels. This can be used to help establish the needed molded dimensions and guide the initial selection of block coefficient. Generally, the coefficient C_{OWT} increases with both ship size and block coefficient. Typical ranges for C_{OWT} defined relative to both cargo deadweight and total deadweight are shown in Table 11.1 for classes of commercial vessels.

If the vessel is *volume limited*, as are most other vessels today, the basic sizing will be controlled by the need to provide a required useful hull volume Y'u' Watson (18) notes that the transition from *weight limited* to *volume limited* comes when the cargo (plus required segregated ballast) stowage factor is about 1.30 m^3/t or inversely when the cargo (plus required segregated ballast) density is about 0.77 *tlm*³· The size of some vessels is set more by the required total hull or deck length than the required volume. On military vessels, the summation of deck requirements for sensors, weapon systems, catapults, elevators, aircraft parking, etc. may set the total vessel length and beam. The vessel sizing must then be iterated to achieve a balance between the required and available hull volume (or length), equation 2. Parametric volume as well as parametric weight models are then needed. The balance of weight and displacement in equation 1 then yields a design draft that is typically less than that permitted by freeboard requirements. The overall approach of moving from an assumed length to other dimensions and block coefficient remains the same, except that in this case hull depth becomes a critical parameter through its control of hull volume. Draft is implicit in equation 2 and is, thus, set by equation 1.

From a design strategy viewpoint, a third class of vessels could be those with functions or requirements that tend to directly set the overall dimensions.

These might be called *constraint-limited* vessels. Benford called some of these vessels *rules or paragraph vessels* where a paragraph of the regulatory requirements, such as the tonnage rules or a sailing yacht racing class rule, dictates the strategy for the primary dimension selection. Watson and Gilfillan (1) use the term *linear dimension* vessel when the operating environment constraints or functional requirements tend to set the basic dimensions. Watson includes containerships in this category since the container stack cross-section essentially sets the beam and depth of the hull. Classic examples would be Panamax bulk carriers, St. Lawrence Seaway-size bulk carriers, or the largest class of Great Lakes bulk carriers. These latter vessels essentially all have (L, B, T) = (304.8 m, 32.0 m, 8.53 m), the maximum dimensions allowed at the Poe Lock at Sault Ste. Marie, MI.

11.2.4 Relative Cost of Ship Parameters

In making initial sizing decisions, it is necessary to consider the effect of the primary ship parameters on resistance, maneuvering, and seakeeping performance; the project constraints; and size-related manufacturing issues. It is also necessary to consider, in general, the relative cost of ship parameters. This general effect was well illustrated for large ships by a study performed in the 1970s by Fisher (25) on the relative cost of length, beam, depth, block coefficient and speed of a 300 m, 148000 DWT, 16.0 knot diesel ore carrier and a 320 m, 253 000 DWT, 14.4 knot steam VLCC crude oil tanker. Fisher's Table II.II shows the incremental change in vessel capital cost that would result from a 1% change in length, beam, depth, block coefficient, or speed.

TABLE 11.I Typical Deadweight Coefficient Ranges

Vessel Type	$C_{cargo\ DWT}$	$C_{total\ DWT}$
Large tankers	0.85–0.87	0.86–0.89
Product tankers	0.77–0.83	0.78–0.85
Container ships	0.56–0.63	0.70–0.78
Ro-Ro ships	0.50–0.59	—
Large bulk carriers	0.79–0.84	0.81–0.88
Small bulk carriers	0.71–0.77	—
Refrigerated cargo ships	0.50–0.59	0.60–0.69
Fishing trawlers	0.37–0.45	—

Note that one could choose to change the length, beam, or block coefficient to achieve a 1% change in the displacement of the vessel. The amounts of these incremental changes that are changes in the steel, outfit, and machinery costs are also shown. One can see in Table II.II that a 1% change in length results in about a 1% change in capital cost.

Further in Table II.II, a 1% increase in beam increases the cost 0.78% for the ore carrier and 0.58% for the VLCC. A 1% increase in depth increases the cost 0.24% for the ore carrier and 0.40% for the VLCC. The 1% block coefficient change is only about one fifth as expensive as a 1% length change. The relative cost of a 1% speed change is a 1% ship cost change for the ore carrier and only a 0.5% ship cost change for the relatively slower tanker. Thus, it is five times more expensive in terms of capital cost to increase displacement by changing length than by changing block coefficient.

Ship dimension, block coefficient, and speed changes will obviously affect hull resistance, fuel consumption, and operating costs as well as vessel capital cost so a complete assessment needs to consider how the Required Freight Rate (RFR) would be affected by these changes. Table II.III shows the incremental change in vessel RFR that would result from a 1% change in length, beam, depth, block coefficient, or speed. A 1% change in ship length would result in a 1.2% increase in RFR for the ore carrier and a 1.1% change in the RFR for the VLCC. A 1% increase in beam increases the RFR 0.9% for the ore carrier and 0.6% for the VLCC. A 1% change in depth and block coefficient have, respectively, about 0.27 and about 0.20 as much impact on RFR as a 1% change in length. Thus, if one of these designs needed 1% more displacement, the most economic way to achieve this change would be to increase block coefficient 1%, with a I% beam change second. The most economic way to decrease displacement by 1% would be to reduce the length 1%. When the impact on fuel cost and other operating costs are considered, a 1% change in ship speed will have greater impact resulting in about a 1.8% change in RFR for either type of vessel.

11.2.5 Initial Dimensions and Their Ratios

A recommended approach to obtain an initial estimate of vessel length, beam, depth, and design draft is to use a dataset of similar vessels, if feasible, to obtain guidance for the initial values. This can be simply by inspection or regression equations can be developed from this data using primary functional requirements, such as cargo deadweight and speed, as independent variables. Development of these equations will be discussed further in Section 11.5. In other situations, a summation of lengths for various volume or weather deck needs can provide a starting point for vessel

TABLE 11.11 Effects of Incremental Changes in Parameters on Capital Cost 1251

	Percent of Total		*L*		*B*		*D*		C_B		V_k	
Category	*Ore Carrier*	*VLCC Tanker*	*Ore Carrier*	*VLCC Tanker*	*Ore Carrier*	*VLCC Tanker*	*Ore Carrier*	*VLCC Tanker*	*Ore Carrier*	*VLCC Tanker*	*Ore Carrier*	*VLCC Tanker*
Steel	28	41	0.47	0.81	0.30	0.43	0.24	0.38	0.11	0.17	–	–
Outfit	26	22	0.27	0.06	0.27	0.04	–	0.02	–	0.01	–	–
Machinery	30	20	0.29	0.14	0.21	0.11	–	–	0.07	0.04	1.01	0.50
Misc/ovhd	16	17	–	–	–	–		–		–	–	–
Total	100	100	1.03	1.01	0.78	0.58	0.24	0.40	0.18	0.22	1.01	0.50

Incremental changes in Total Capital Costs as percent of Origianl Capital Cost due to a 1% increase in the parameter.

TABLE 11.111 Effects of Incremental Changes in Parameters on Required Freight Rate 1251

	Percent of Total		*L*		*B*		*D*		C_B		V_k	
Category	*Ore Carrier*	*VLCC Tanker*	*Ore Carrier*	*VLCC Tanker*	*Ore Carrier*	*VLCC Tanker*	*Ore Carrier*	*VLCC Tanker*	*Ore Carrier*	*VLCC Tanker*	*Ore Carrier*	*VLCC Tanker*
Capital Recov.	62	54	0.84	0.63	0.59	0.32	0.17	0.21	0.12	0.11	0.98	0.36
Fixed Annual Costs*	21	22	0.20	0.20	0.14	0.11	0.06	0.08	0.03	0.04	0.26	0.11
Voyage Costs	17	24	0.18	0.26	0.15	0.17	0.09	0.01	0.10	0.05	0.54	1.30
Total	100	100	1.22	1.09	0.88	0.60	0.32	0.30	0.25	0.20	1.78	1.77

* Including crew, stores and supplies.
Incremental changes in Required Freight Rates as percent of origianl Required Freight Rate due to a 1% increase in the parameter, using CR(15%, 10 years) = 0.199.

length. Since the waterline length at the design draft T is a direct factor in the displacement and resistance of the vessel, LWL is usually the most useful length definition to use in early sizing iterations.

The typical primary influence of the various hull dimensions on the function/performance of a ship design is summarized in Table ll.IV. The parameters are listed in a typical order of importance indicating an effective order for establishing the parameters. Of course, length, beam, and draft all contribute to achieving the needed displacement for the hull. The primary independent sizing variable is typically taken as length. With length estimated, a beam that is consistent with discrete cargo needs and/or consistent with the length can be selected. With a candidate length and beam selected, a depth that is consistent with functional needs can be selected. The initial draft can then be selected. In all cases, of course, dimensional constraints need to be considered.

Watson (18) notes that with a target displacement and an acceptable choice of vessel length-beam ratio, beam-draft ratio, and block coefficient based upon vessel type and Froude number, equation 1 becomes:

$$L = \{[\Delta\,(L/B)^2\,B/T)/(\gamma\,C_B\,(1 + s)]\}^{1/3} \qquad [4]$$

This approach can provide a way to obtain an initial estimate of the vessel length.

A number of approximate equations also exist in the literature for estimating vessel length from other ship characteristics. For illustration, a classic example is Posdunine's formula:

TABLE 11.1V Primary Influence of Hull Dimensions

Parameter	*Primary Influence of Dimensions*
length	resistance, capital cost, maneuverability, longitudinal strength, hull volume, seakeeping
beam	transverse stability, resistance, maneuverability, capital cost, hull volume
depth	hull volume, longitudinal strength, transverse stability, capital cost, freeboard
draft	displacement, freeboard, resistance, transverse stability

$$L\ (m) = C\ [V_k/(V_k + 2)]^2\ \Delta^{1/3} \quad [5]$$

where displacement is in tonnes and the speed is in knots (as indicated by the subscript k) and the coefficient C can be generalized from similar vessels. Typical coefficient C ranges are 7.1 to 7.4 for single screw vessels of 11 to 18.5 knots, 7.4 to 8.0 for twin screw vessels of 15 to 20 knots, and 8.0 to 9.7 for twin screw vessels of 20 to 30 knots

The frictional resistance of a hull increases with length since the wetted surface increases faster with length than the frictional resistance coefficient declines with Reynolds number. The wave resistance, however, decreases with length. The net effect is that resistance as a function of ship length typically exhibits a fairly broad, flat minimum. Therefore, since the hull cost increases with length, an economic choice is usually a length at the lower end of this minimum region where the resistance begins to increase rapidly with further length reduction. Below this length higher propulsion requirements and higher operating costs will then offset any further reduction in hull capital cost.

11.2.5.1 Length-beam ratio UB

Various non-dimensional ratios of hull dimensions can be used to guide the selection of hull dimensions or alternatively used as a check on the dimensions selected based upon similar ships, functional requirements, etc. Each designer develops his or her own preferences, but generally the length-beam ratio LIB, and the beam-depth ratio *BID,* prove to be the most useful.

The length-beam ratio can be used to check independent choices of Land B or with an initial L, a choice of a desired LIB ratio can be used to obtain an estimated beam B. The LIB ratio has significant influence on hull resistance and maneuverability-both the ability to turn and directional stability. With the primary influence of length on capital cost, there has been a trend toward shorter wider hulls supported by design refinement to ensure adequate inflow to the propeller. Figure 11.1 from Watson (18) shows the relationship ofL and B for various types of commercial vessels. Note that in this presentation, rays from the origin are lines of constant LIB ratio. From this Watson and Gilfillan (1) recommended:

LIB = 4.0, for L ::;30 m
= 4.0 + 0.025 (L - 30), for 30 ::;L ::;130 m [6]
= 6.5, for 130 m ::;L

They also noted a class oflarger draft-limited vessels that need to go to higher beam leading to a lower LIB ratio of about 5.1. Watson (18) noted that recent large tankers had LIB ""5.5 while recent reefers, containerships, and bulk carriers had LIB "" 6.25. This guidance is useful, but only an indication of general design trends today. Similar information could be developed for each specific class of vessels of interest. Specific design requirements can lead to a wide range of LIB choices. Great Lakes 300m ore carriers have LIB = 9.5 as set by lock dimensions.

Icebreakers tend to be short and wide to have good maneuverability in ice; and to break a wide path for other vessels leading to LIB values of about 4.0. Similarly, the draft -limited Ultra Large Crude Carriers (ULCCs) have had LIB ratios in the range of 4.5 to 5.5. The recent *Ramform* acoustic survey vessels have an LIB of about 2.0 (see Chapter 42, Subsection 42.1.1.2 and Chapter 30, Table 30.11). At the high end, World War II Japanese cruisers, such as the *Furutaka* class, had an LIB of 11.7 and not surprisingly experienced stability problems due to their narrow hulls.

11.2.5.2 Beam-depth ratio *BID*

The next most important non-dimensional ratio is the beam-depth ratio *BID.* This provides effective early guidance on initial intact transverse stability. In early design, the transverse metacentric height is usually assessed using:

$GM_T = KB + BM_T$ -1.03 KG:2::req'd GMT [7]

where the 3% (or similar) increase in KG is included to account for anticipated free surface effects. Using parametric models that will be presented below, it is possible to estimate the partial derivatives of GMT with respect to the primary ship dimensions. Using parametric equations for form coefficients and characteristics for a typical Seaway size bulk carrier for illustration this yields:

$$\partial GM_T/\partial B = +0.48$$
$$\partial GM_T/\partial D = -0.70$$
$$\partial GM_T/\partial T = -0.17$$
$$\partial GM_T/\partial L = +0.00$$
$$\partial GM_T/\partial C_B = +1.34$$

The value of the transverse metacentric radius BM_T is primarily affected by beam (actually $B^2/C_B\ T$) while the ver-

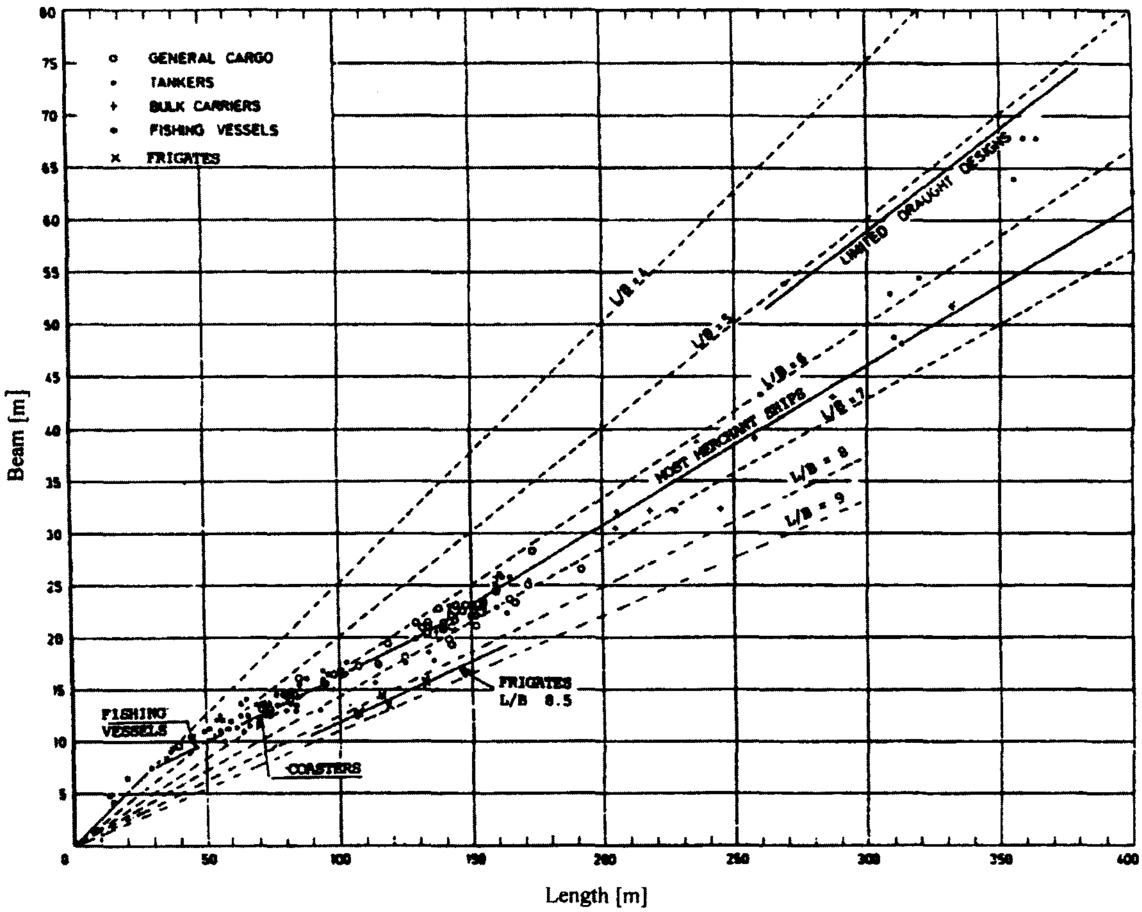


Figure 11.1 Beam versus Length (18)

tical center of gravity KG is primarily affected by depth so the *BID* ratio gives early guidance relative to potential stability problems. Watson (18) presents data for commercial vessels included in Figure 11.2.

From this data, Watson and Gilfillan (1) concluded that weight limited vessels had *BID* "" 1.90 while stability constrained volume limited vessels had *BID* "" 1.65. Watson (18) noted that recent large tankers had *BID* "" 1.91; recent bulk carriers had *BID* "" 1.88, while recent reefers and containerships had *BID* "" 1.70. Extreme values are Great Lakes iron ore carriers with *BID* = 2.1 and ULCCs with values as high as 2.5.

Early designs should proceed with caution if the *BID* is allowed to drop below 1.55 since transverse stability problems can be expected when detailed analyses are completed.

11.2.5.3 Beam-draft ratio BIT

The third most important nondimensional ratio is the beam-draft ratio *BIT.* The beam-draft ratio is primarily important through its influence on residuary resistance, transverse stability, and wetted surface. In general, values range between 2.25 ~ B *IT* ~ 3.75, but values as high as 5.0 appear in heavily draft-limited designs. The beam-draft ratio correlates strongly with residuary resistance, which increases for large *BIT.* Thus, *BIT* is often used as an independent variable in residuary resistance estimating models. As *BIT* becomes low, transverse stability may become a problem as seen from the above example of partial derivatives. Saunders (26) presented data for the non-dimensional wetted surface coefficient C_S = Sh/CVL) for the Taylor Standard Series hulls that is instructive in understanding the influence of *BIT* on wetted surface and, thus particularly, frictional resistance. Saunders' contour plot of C_S versus C_M and *BIT* is shown in Figure 11.3. One can see that the minimum wetted surface for these hulls is achieved at about C_M = 0.90 and *BIT* = 3.0. The dashed line shows the locus of *BIT* values which yield the minimum wetted surface hulls for varying C_M and is given by:

$$B/T|_{\min C_S} = 5.93 - 3.33\, C_M \qquad [8]$$

In their SNAME-sponsored work on draft-limited conventional single screw vessels, Roseman et al (27) recommended that the beam-draft ratio be limited to the following maximum:

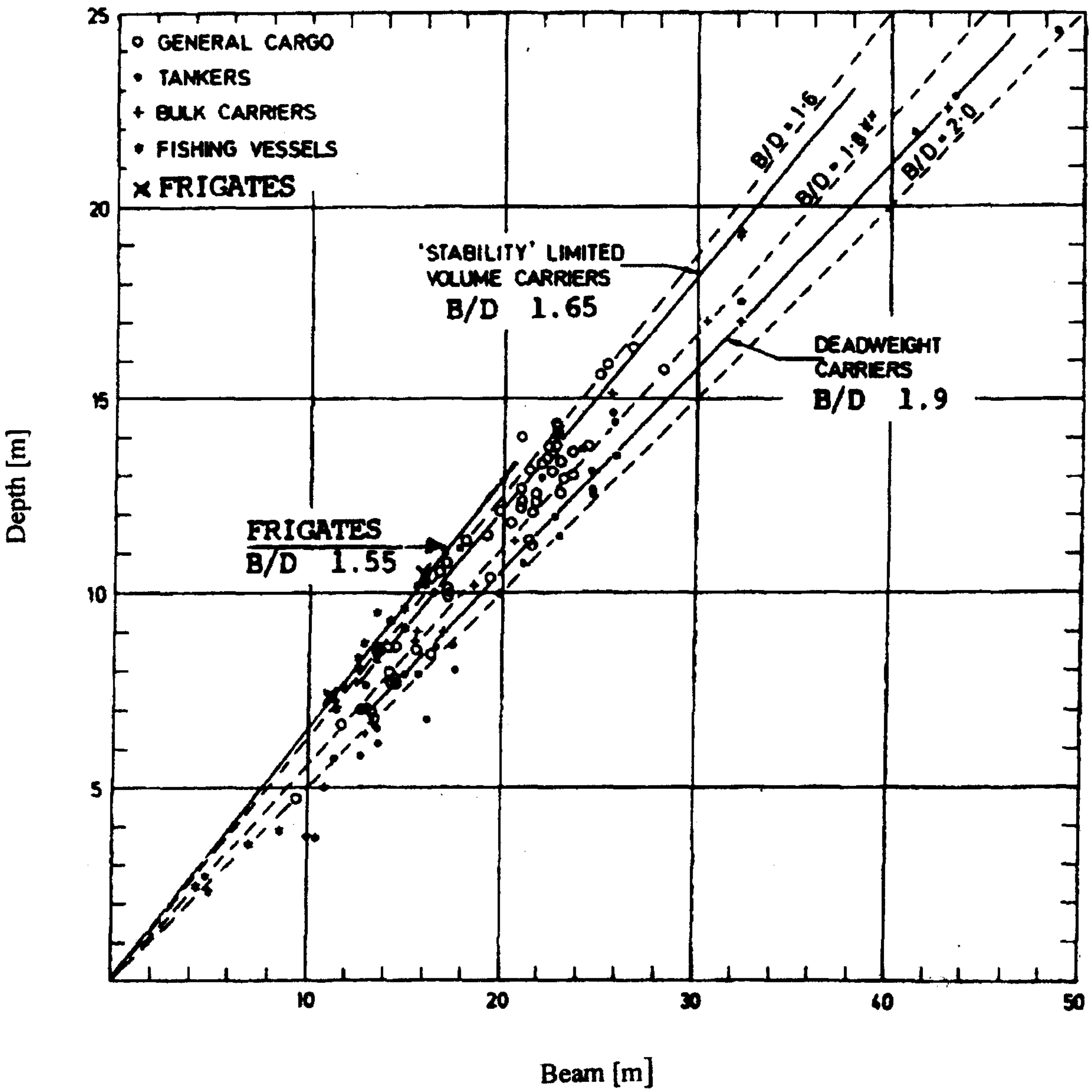


Figure 11.2 Depth versus Beam (18)

$$(B/T)_{max} = 9.625 - 7.5\ C_B \qquad [9]$$

in order to ensure acceptable flow to the propeller on large draft-limited vessels.

11.2.5.4 Length-depth ratio LJD

The length-depth ratio LID is primarily important in its influence on longitudinal strength. In the length range from about 100 to 300 m, the primary loading vertical wave bending moment is the principal determinant of hull structure. In this range, the vertical wave bending moment increases with ship length. Local dynamic pressures dominate below about 100 meters. Ocean wavelengths are limited, so beyond 300 meters the vertical wave bending moment again becomes less significant. The ability of the hull to resist primary bending depends upon the midship section moment of inertia, which varies as Band 0^3. Thus, the ratio LID relates to the ability of the hull to be designed to resist longitudinal bending with reasonable scantlings. Classification society requirements require special consideration when the LID ratio lies outside the range assumed in the development of their rules.

11.2.6 Initial Hull Form Coefficients

The choice of primary hull form coefficient is a matter of design style and tradition. Generally, commercial ships tend to be developed using the block coefficient C_B as the pri-

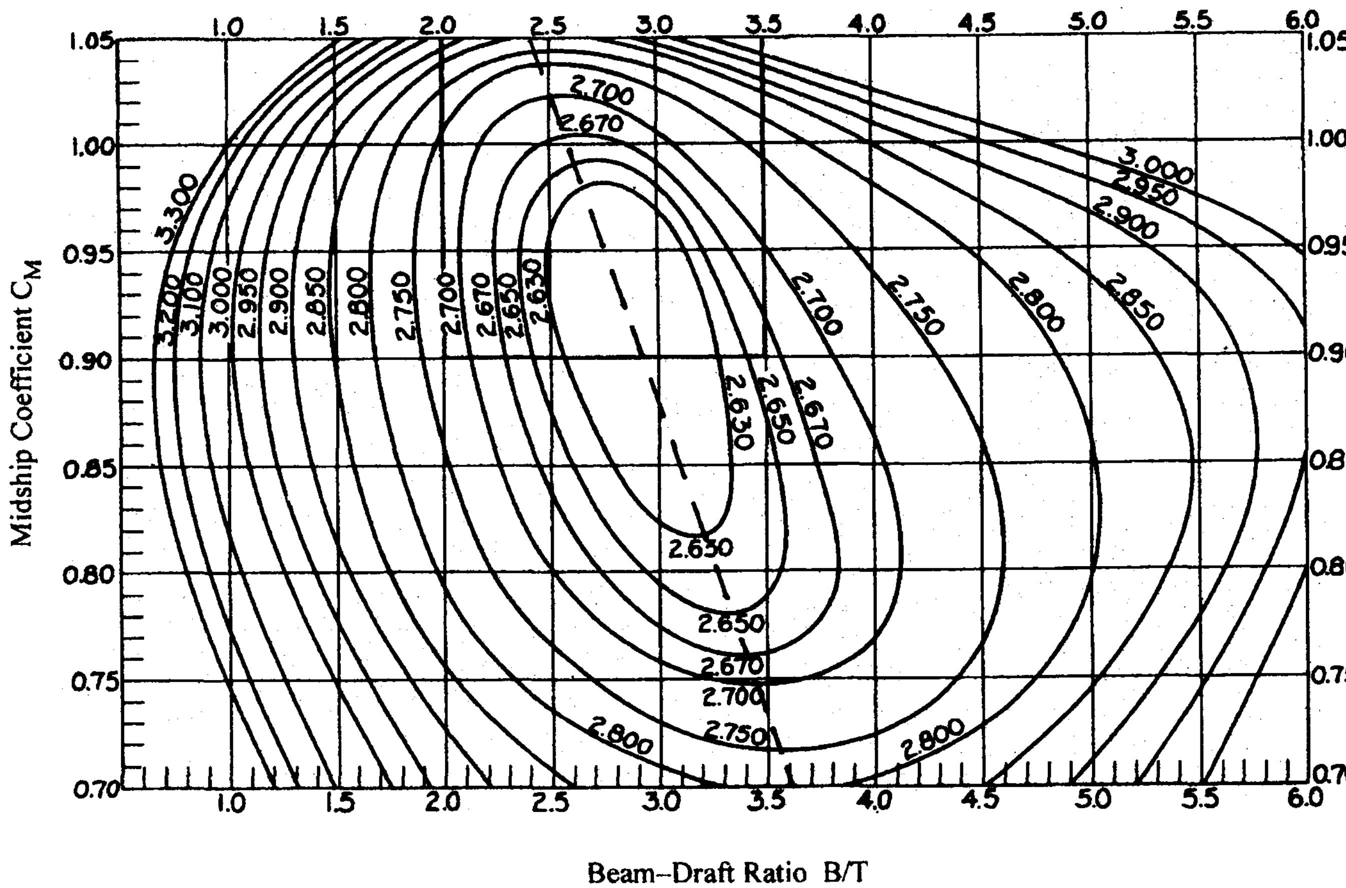


Figure 11.3 Wetted Surface Coefficient for Taylor Standard Series Hulls (26)

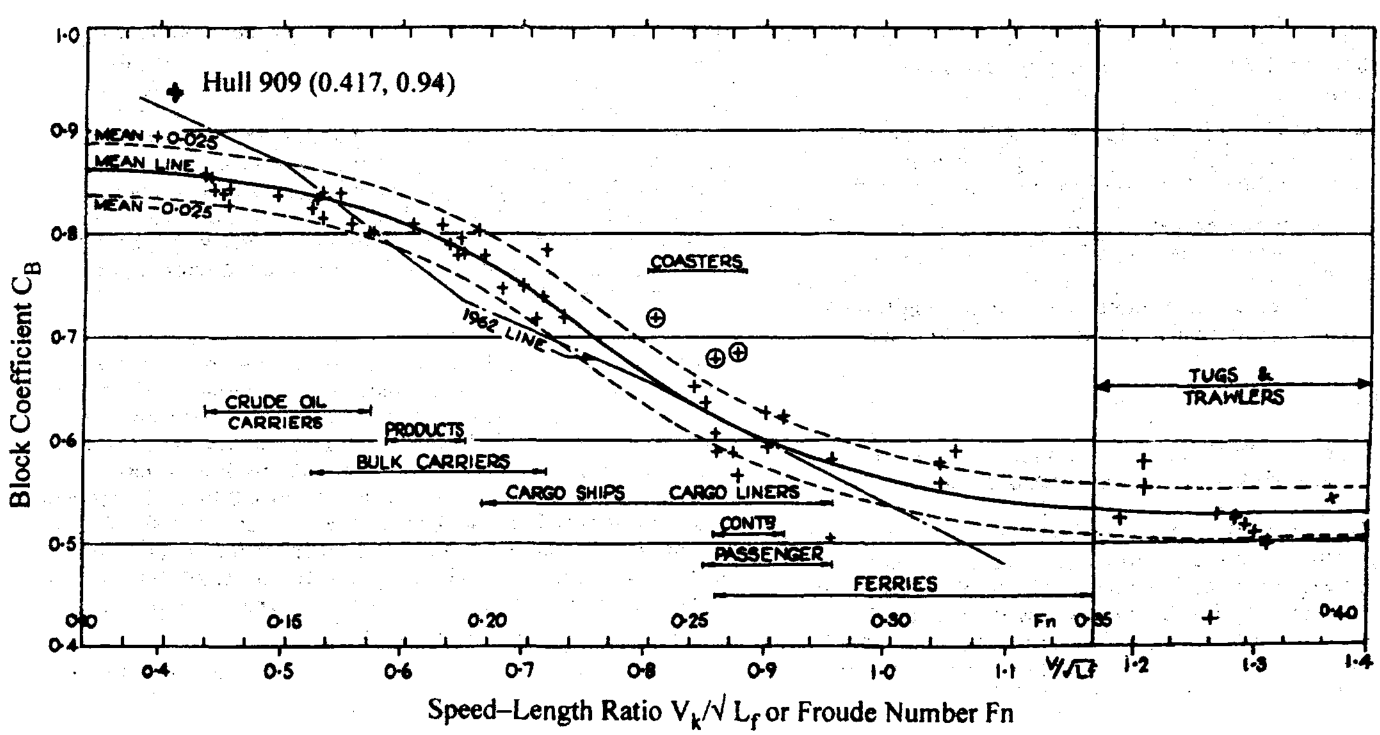


Figure 11.4 Watson and Gilfillan Recommended Block Coefficient (1,18)

mary form coefficient, while faster military vessels tend to be developed using the longitudinal prismatic C_P as the form coefficient of greatest importance. Recall that through their definitions, the form coefficients are related by dual identities, one for the longitudinal direction and one for the vertical direction, they are:

$$C_B \equiv C_P\, C_X \qquad [10]$$

$$C_B \equiv C_{VP}\, C_{WP} \qquad [11]$$

Thus with an estimate or choice of any two coefficients in either equation, the third is established by its definition. A designer cannot make three independent estimates or choices of the coefficients in either identity.

11.2.6.1 Block coefficient C_S

The block coefficient C_B measures the fullness of the submerged hull, the ratio of the hull volume to its surrounding parallelepiped LBT. Generally, it is economically efficient to design hulls to be slightly fuller than that which will result in minimum resistance per tonne of displacement. The most generally accepted guidance for the choice of block coefficient for vessels in the commercial range of hulls is from Watson and Gilfillan (1) as shown in Figure 11.4. This useful plot has the dimensional speed length ratio V;-YLf (with speed in knots and length in feet) and the Froude number Fn as the independent variables. Ranges of typical classes of commercial vessels are shown for reference. The recommended C_B is presented as a mean line and an acceptable range of ± 0.025. Watson's recommended C_B line from his earlier 1962 paper is also shown. This particular shape results because at the left, slow end hulls can have full bows, but still need fairing at the stem to ensure acceptable flow into the propeller leading to a practical maximum recommended C_B of about 0.87. As a practical exception, data for the 300 m Great Lakes ore carrier *James R. Barker* (hull 909) is shown for reference. **At** the right, faster end the resistance becomes independent of C_B and, thus, there appears to be no advantage to reducing C_B below about 0.53.

In his sequel, Watson (28) noted that the recommended values in the 0.18 :::Fn :::0.21 range might be high. This results because the bulk carriers considered in this range routinely claim their speed as their maximum speed (at full power using the service margin) rather than their service or trial speed as part of tramp vessel marketing practices. Independent analysis tends to support this observation. Many designers and synthesis models now use the Watson and Gilfillan mean line to select the initial C_B given Fn. This is based upon a generalization of existing vessels, and primarily reflects smooth water powering. Any particular design has latitude certainly within at least the ± 0.025 band in selecting the needed C_B, but the presentation provides primary guidance for early selection. To facilitate design, Towsin in comments on Watson's sequel (28) presented the following equation for the Watson and Gilfillan mean line:

$$C_B = 0.70 + 0.125\ \tan^{-1}\ [(23 - 100\ Fn)/4] \qquad [12]$$

(In evaluating this on a calculator, note that the radian mode is needed when evaluating the arctan.)

Watson (18) notes that a study of recent commercial designs continues to validate the Watson and Gilfillan mean line recommendation, or conversely most designers are now using this recommendation in their designs. Schneekluth and Bertram (17) note that a recent Japanese statistical study yielded for vessels in the range 0.15 :::Fn :::0.32:

$$C_B = -4.22 + 27.8\sqrt{Fn} - 39.1\ Fn + 46.6\ Fn^3 \qquad [13]$$

Jensen (29) recommends current best practice in German designs, which appears to coincide with the Watson and Gilfillan mean line. Figure 11.5 shows the Watson and Gilfillan mean line equation 12 and its bounds, the Japanese study equation 13, and the Jensen recommendations for comparison. Recent Japanese practice can be seen to be somewhat lower than the Watson and Gilfillan mean line above Fn ""0.175.

The choice of C_B can be thought of as selecting a fullness that will not result in excessive power requirements for the Fn of the design. As noted above, designs are generally selected to be somewhat fuller than the value that would result in the minimum resistance per tonne. This can be illustrated using Series 60 resistance data presented by Telfer in his comments on Watson and Gilfillan (1). The nondimensional resistance per tonne of displacement for Series 60 hulls is shown in Figure 11.6 as a function of speed length ratio V;-YLf with the block coefficient C_B the parameter on curves. The dashed line is the locus of the minimum resistance per tonne that can be achieved for each speed-length ratio.

Fitting an approximate equation to the dashed locus in Figure 11.6 yields the block coefficient for minimum resistance per tonne:

$$C_B = 1.18 - 0.69\ V_k/\sqrt{L_f} \qquad [14]$$

This equation can be plotted on Figure 11.4 where it can be seen that it roughly corresponds to the Watson and Gilfillan mean line – 0.025 for the speed length ratio range $0.5 \le V_k/\sqrt{L_f} \le 0.9$.

One of the many classic formulae for block coefficient can be useful in the intermediate $0.50 \le V_k/\sqrt{L_f} \le 1.0$ region. Alexander's formula has been used in various forms since about 1900:

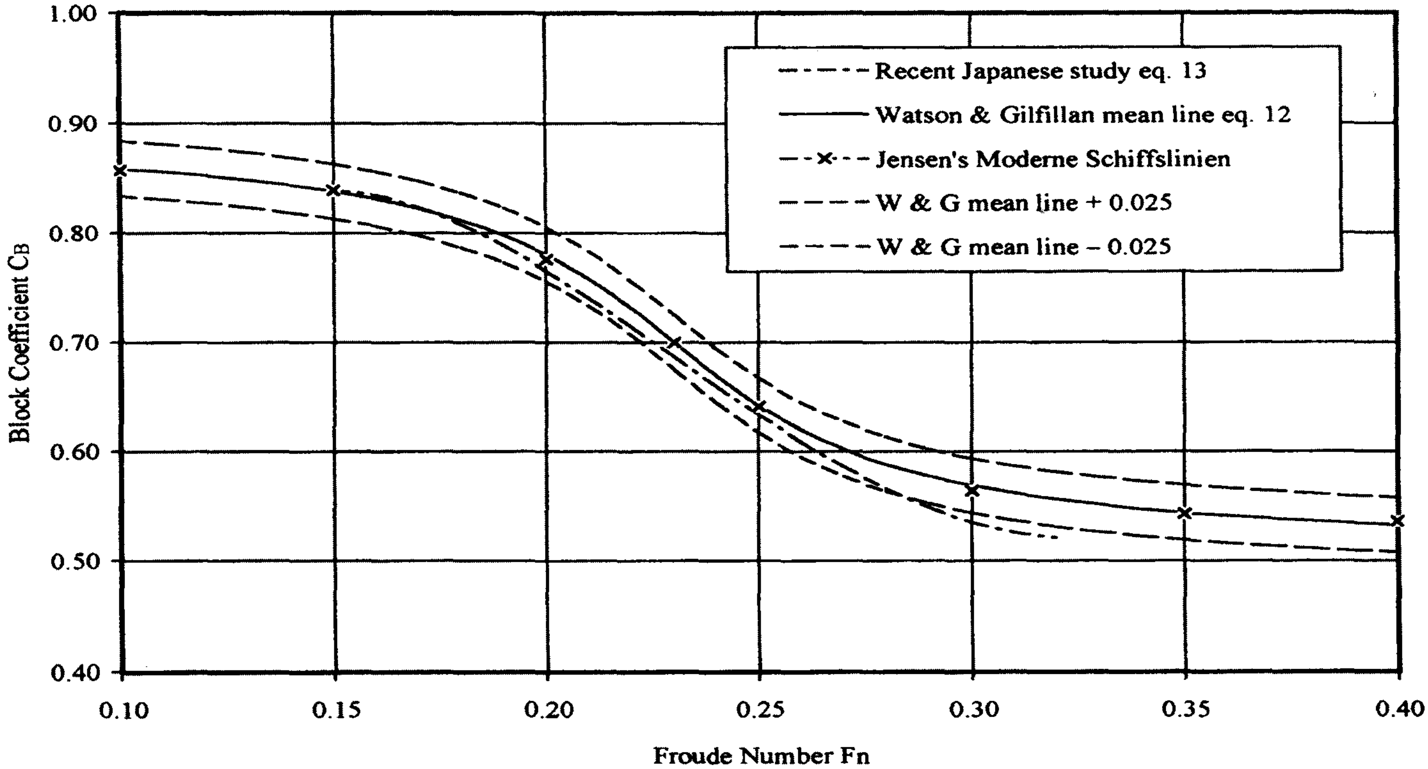


Figure 11.5 Comparison of Recent Block Coefficient Recommendations

$$C_B = K - 0.5\, V_k/\sqrt{L_f} \qquad [15]$$

where $K = 1.33 - 0.54\, V_k/\sqrt{L_f} + 0.24(V_k/\sqrt{L_f})^2$, is recommended for merchant vessels. Other examples are available in the literature for specific types of vessels.

11.2.6.2 Maximum section coefficient C_X and midship section coefficient C_M

The midship and maximum section coefficient $C_M \approx C_X$ can be estimated using generalizations developed from existing hull forms or from systematic hull series. For most commercial hulls, the maximum section includes amidships.

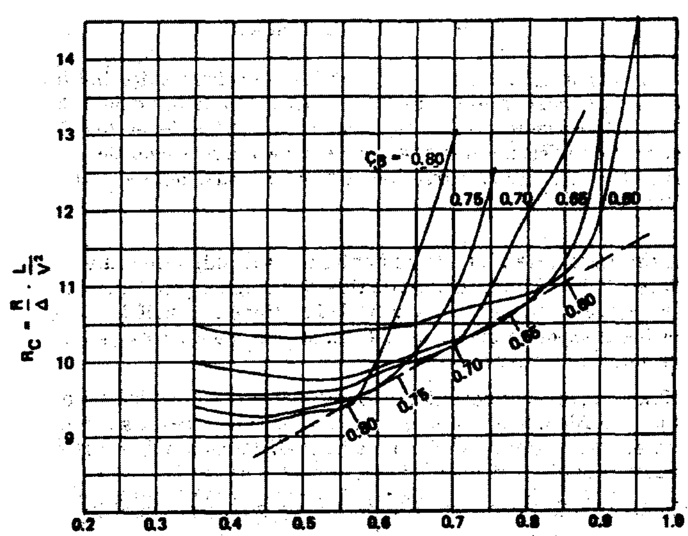
For faster hulls, the maximum section may be significantly aft of amidships. Recommended values for C_M are:

$$C_M = 0.977 + 0.085\,(C_B - 0.60) \qquad [16]$$

$$C_M = 1.006 - 0.0056\, C_B^{-3.56} \qquad [17]$$

$$C_M = (1 + (1 - C_B)^{3.5})^{-1} \qquad [18]$$

Benford developed equation 16 from Series 60 data. Equations 17 and 18 are from Schneekluth and Bertram (17) and attributed to Kerlen and the HSVA Linienatlas, respectively. Jensen (29) recommends equation 18 as current best practice in Germany. These recommendations are presented in Figure 11.7 with a plot of additional discrete rec-



Speed–Length Ratio $V_k/\sqrt{L_f}$

Figure 11.6 Resistance per Tonne for Series 60 (28)

ommendations attributed by Schneekluth and Bertram to van Lammeren. If a vessel is to have a full midship section with no deadrise, flat of side, and a bilge radius, the maximum section coefficient can be easily related to the beam, draft, and the bilge radius r as follows:

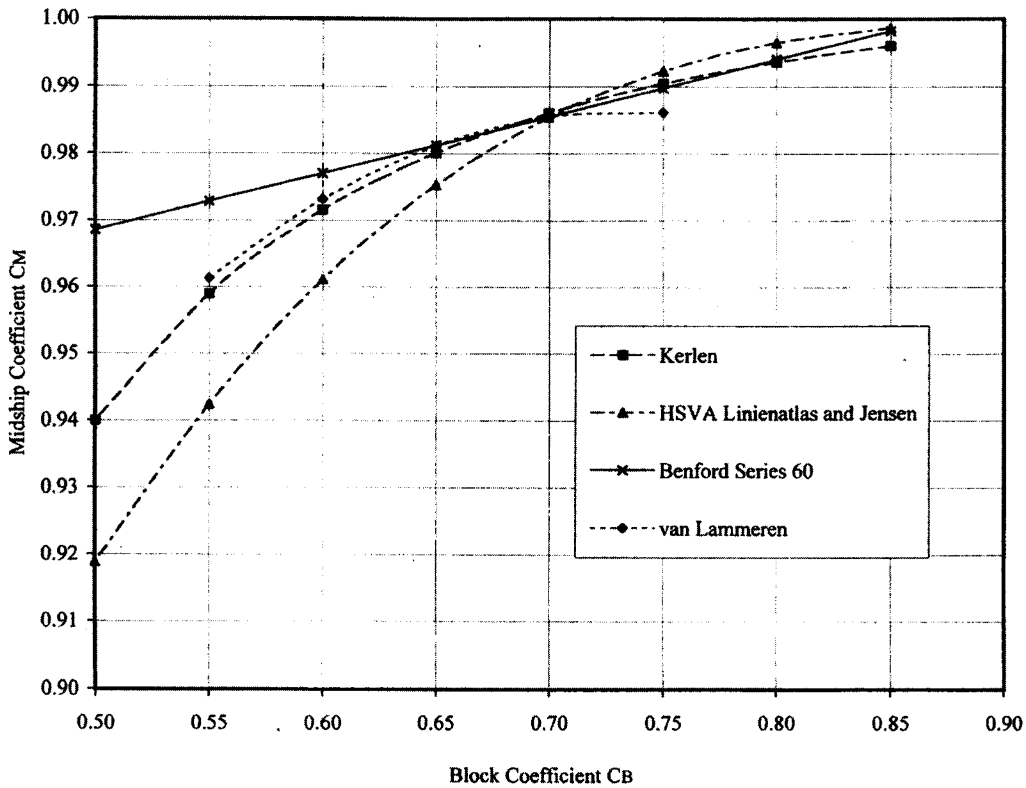


Figure 11.7 Recommended Midship Coefficients

$$C_M = 1 - 0.4292\, r^2 / BT \qquad [19]$$

If a vessel is to have a flat plate keel of width K and a rise of floor that reaches F at B/2, this becomes:

$$C_M = 1 - \{F[(B/2 - K/2) - r^2 / (B/2 - K/2)] + 0.4292\, r^2\}/BT \qquad [20]$$

Producibility considerations will often make the bilge radius equal to or slightly below the innerbottom height hdb to facilitate the hull construction. In small to medium sized vessels, the bilge quarter circle arc length is often selected to be the shipyard's single standard plate width. Using *BIT* = 3.0 and an extreme r = T, equation 19 yields a useful reference lower bound of C_M = 0.857. Using *BIT* = 2.0 and r = T giving a half circle hull section, this yields C_M = 0.785.

11.2.6.3 Longitudinal prismatic coefficient C_P

The design of faster military and related vessels typically uses the longitudinal prismatic coefficient C_P, rather than C_B, as the primary hull form coefficient. The longitudinal prismatic describes the distribution of volume along the hull form. A low value of C_P indicates significant taper of the hull in the entrance and run. A high value of C_P indicates a more full hull possibly with parallel midbody over a significant portion of the hull. If the design uses C_B as the principal hull form coefficient and then estimates Cx, C_P can be obtained from the identity of equation 10. If C_P is the principal hull form coefficient, the remaining C_B or C_X could then be obtained using equation 10.

The classic principal guidance for selecting the longitudinal prismatic coefficient C_P was presented by Saunders (26), Figure 11.8. This plot presents recommended design lanes for C_P and the displacement-length ratio in a manner similar to Figure 1104. Again, the independent variable is the dimensional speed length ratio (Taylor Quotient) V.;..JL$_f$ or the Froude number Fn. This plot is also useful in that it shows the regions of residuary resistance humps and hollows, the regions of relatively high and low wave resistance due to the position of the crest of the bow wave system relative to the stern. Saunders' design lane is directly comparable to the Watson and Gilfillan mean line ± 0.025 for C_B. Saunders' recommendation remains the principal C_P reference for the design and evaluation of U.S. Naval vessels.

A quite different recommendation for the selection of C_P appeared in comments by D. K. Brown on Andrews (15). The tentative design lane proposed by Brown based

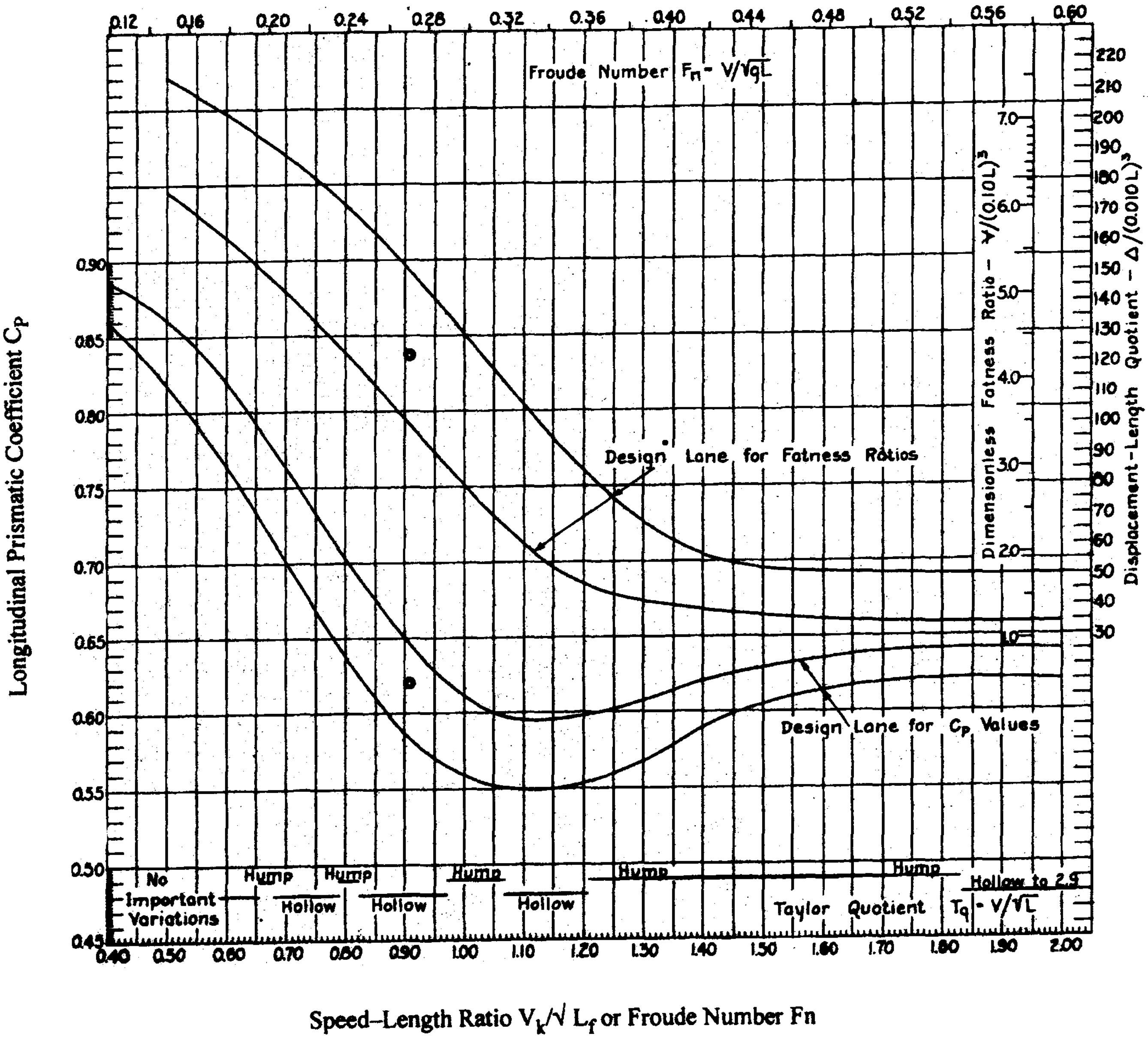


Figure 11.8 Saunders' Design Lanes for Longitudinal Prismatic and Volumetric Coefficient (26)

upon minimization of Froude's circle C (total resistance per tonne divided by circle K squared) is shown in Figure 11.9. This shows a recommended design lane for C_P versus the Froude's circle K and volumetric Froude number F_∇ derived from tests at Haslar. Note that Brown recommends significantly lower values for C_P than recommended by Saunders.

11.2.6.4 Displacement–length ratio and volumetric coefficient C_V

The block coefficient describes the fullness of the submerged hull and the longitudinal prismatic describes the distribution of its volume along the length of the hull for normal hull forms with taper in the entrance and run. But, neither of these reveals a third important characteristic of a hull form. Consider a unit cube and a solid with unit cross-section and length 10. Each would have $C_B = 1$ and $C_P = 1$, but they would obviously have significantly different properties for propulsion and maneuvering. The relationship between volume and vessel length, or its fatness, also needs to be characterized. There are a number of hull form coefficients that are used to describe this characteristic. The traditional English dimensional parameter is the displacement-length ratio = $\Delta/(0.01L_f)^3$, with displacement

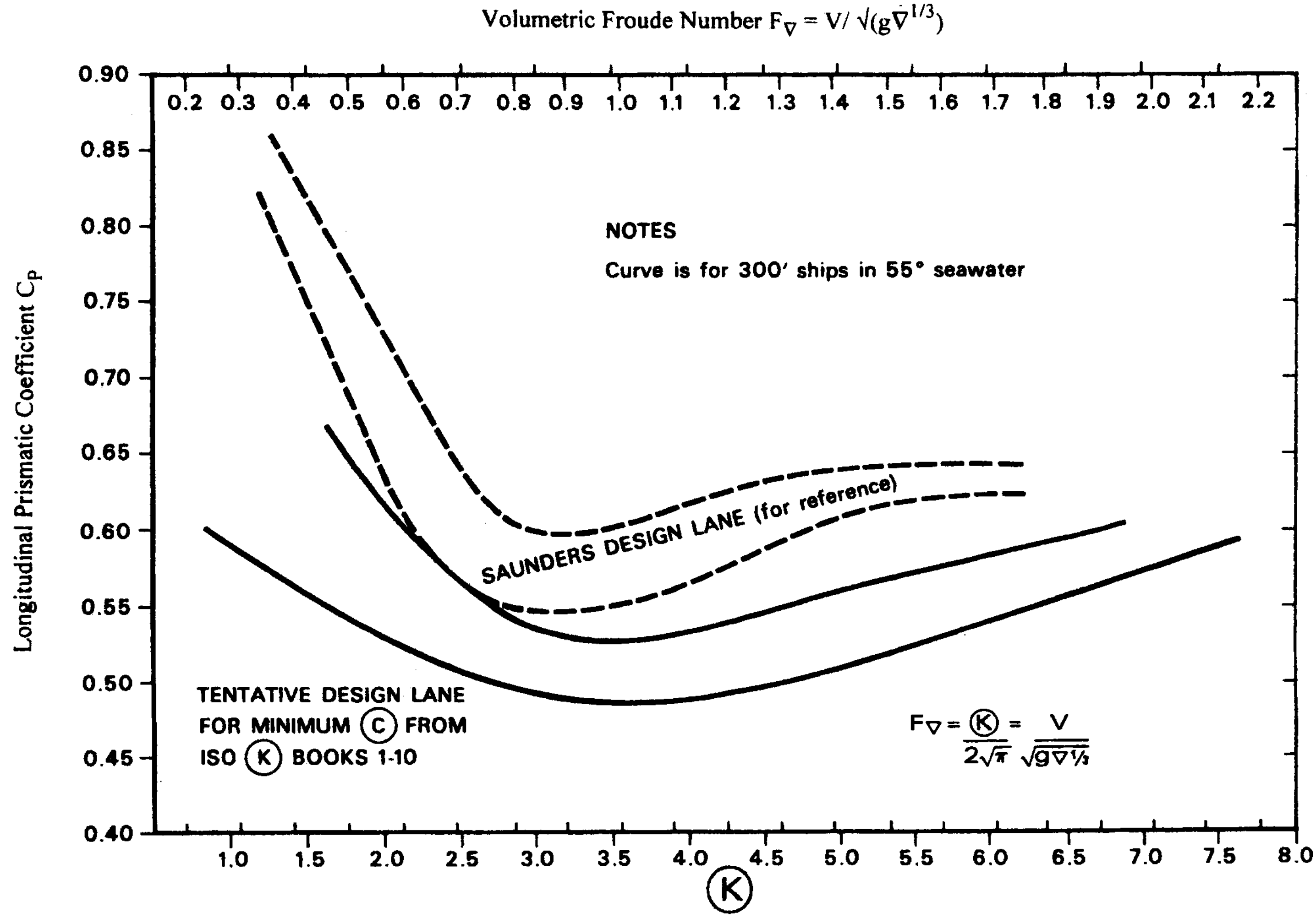


Figure 11.9 Brown's Recommended Design Lane for Longitudinal Prismatic (15)

in long tons and length in feet. Others use a dimensionless fatness ratio $\nabla/(0.10L)^3$ or the volumetric coefficient $C_\nabla = \nabla/L^3$. Traditional British practice uses an inversely related circle M coefficient defined as $L/\nabla^{1/3}$. Saunders recommends design lanes for the first two of these ratios in Figure 11.8. Some naval architects use this parameter as the primary hull form coefficient, in preference to C_B or C_P, particularly in designing tugboats and fishing vessels.

11.2.6.5 Waterplane coefficient C_{WP}

The waterplane coefficient C_{WP} is usually the next hull form coefficient to estimate. The shape of the design waterplane correlates well with the distribution of volume along the length of the hull, so C_{WP} can usually be estimated effectively in early design from the chosen C_P, provided the designer's intent relative to hull form, number of screws, and stern design is reflected. An initial estimate of C_{WP} is used to estimate the transverse and longitudinal inertia properties of the waterplane needed to calculate BM_T and BM_L, respectively. With a C_{WP} estimate, the identity equation 11 can be used to calculate a consistent C_{VP} that can be used to estimate the vertical center of buoyancy KB of the hull.

There is a catalog of models in the literature that allow estimation of C_{WP} from C_P, C_B, or C_B and C_M. These models are summarized in Table 11.V. The first two models are plotted in Figure 11.10 and show that the use of a transom stern increases C_{WP} by about 0.05 to 0.08 at the low C_P values typical of the faster transom stern hulls. It is important to be clear on the definition of stern types in selecting which of these equations to use. Three types of sterns are sketched in Figure 11.11. The cruiser stern gets its name from early cruisers, such as the 1898 British cruiser *Leviathan* used as the parent for the Taylor Standard Series. Cruisers of this time period had a canoe-like stern in which the waterplane came to a point at its aft end. Cruisers of today typically have "hydrodynamic" transom sterns, for improved high-speed resistance, in which the waterplane ends with a finite transom beam at the design waterline at zero speed. Lead-

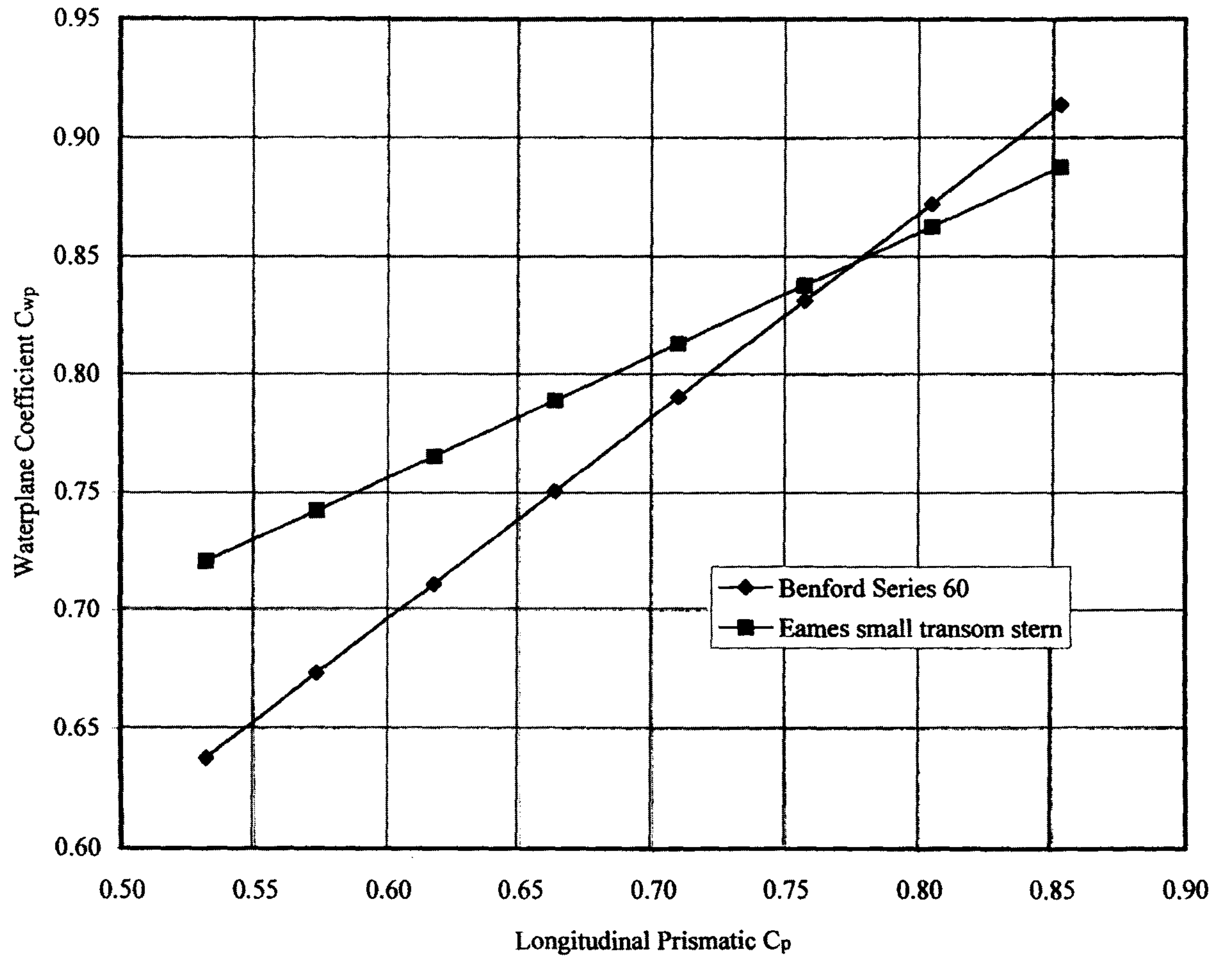


Figure 11.10 Estimates for Waterplane Coefficient C_{WP}

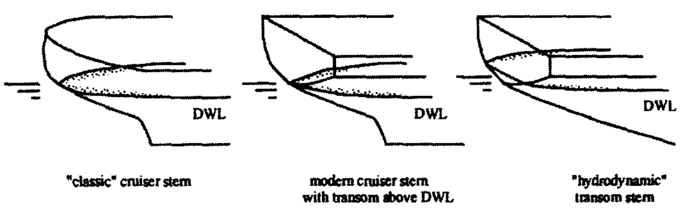


Figure 11.11 Types of Sterns

ing to further potential confusion, most commercial ships today have flat transoms above the waterline to simplify construction and save on hull cost, but these sterns still classify as cruiser sterns *below* the waterline, not hydrodynamic transom sterns.

The fourth through sixth equations in Table 11.V are plotted in Figure 11.12. The effect of the transom stern can be seen to increase C_{WP} about 0.05 in this comparison. The wider waterplane aft typical with twin-screw vessels affects the estimates a lesser amount for cruiser stern vessels. The

TABLE 11.V Design Equations for Estimating Waterplane Coefficient

Equation	*Applicability/Source*
$C_{WP} = 0.180 + 0.860\ C_P$	Series 60
$C_{WP} = 0.444 + 0.520\ C_P$	Eames, small transom stern warships (2)
$C_{WP} = C_B/(0.471 + 0.551\ C_B)$	tankers and bulk carriers (17)
$C_{WP} = 0.175 + 0.875\ C_P$	single screw, cruiser stern
$C_{WP} = 0.262 + 0.760\ C_P$	twin screw, cruiser stern
$C_{WP} = 0.262 + 0.810\ C_P$	twin screw, transom stern
$C_{WP} = C_P^{\ 2/3}$	Schneekluth 1 (17)
$C_{WP} = (1 + 2\ C_B/C_M^{\ 1/2})/3$	Schneekluth 2 (17)
$C_{WP} = 0.95\ C_P + 0.17(1 - C_P)^{1/3}$	U-form hulls
$C_{WP} = (1 + 2\ C_B)/3$	Average hulls, Riddlesworth (2)
$C_{WP} = C_B^{\ 1/2} - 0.025$	V-form hulls

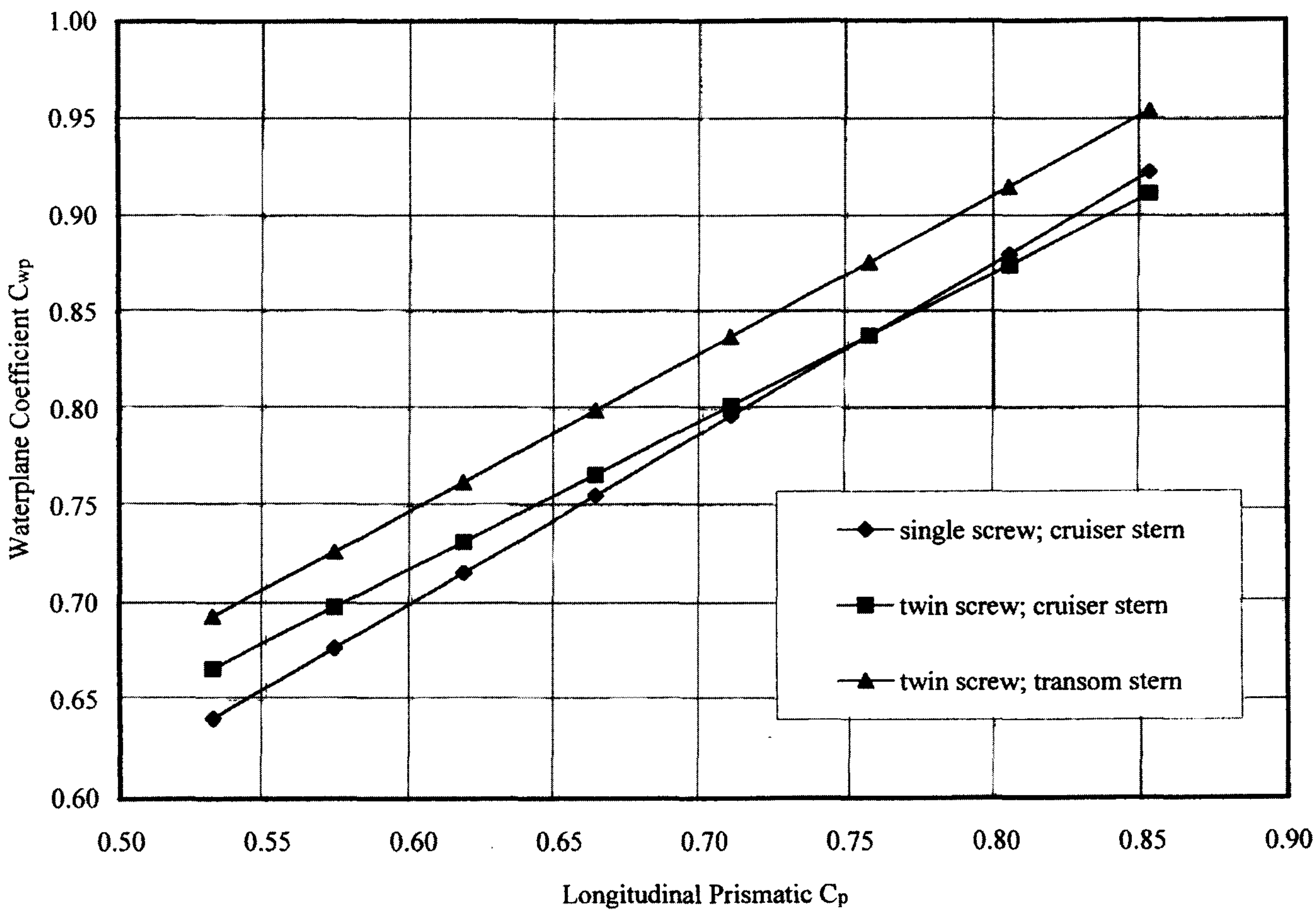


Figure 11.12 Estimates of Waterplane Coefficient C_{WP}—Effect of Stern Type

nineth through eleventh equations in Table 11.V are plotted in Figure 11.13. The choice of a V-shaped rather than a U-shaped hull significantly widens the waterplane resulting in up to a 0.05 increase in C_{WP}. V-shaped hulls typically have superior vertical plane (heave and pitch) seakeeping characteristics, but poorer smooth water powering characteristics leading to an important design tradeoff in some designs.

11.2.6.6 Vertical prismatic coefficient C_{VP}

The vertical prismatic coefficient is used in early design to estimate the vertical center of buoyancy KB needed to assess the initial stability. The vertical prismatic coefficient describes the vertical distribution of the hull volume below the design waterline.

Since conventional hull forms typically have their greatest waterplane area near the water surface, a C_{VP} approaching 0.5 implies a triangular-shaped or V-shaped hull. A C_{VP} approaching 1.0 implies a full, extreme U-shaped hull. Small Waterplane Twin Hull (SWATH) vessels would, obviously, require a unique interpretation of C_{VP}.

The vertical prismatic coefficient C_{VP} inversely correlates with hull wave damping in heave and pitch, thus, low values of C_{VP} and corresponding high values of C_{WP} produce superior vertical plane seakeeping hulls. If a designer were to select C_{VP} to affect seakeeping performance, identity equation 11 can then be used to obtain the consistent value for C_{WP}.

This characteristic can be illustrated by work of Bales (30) in which he used regression analysis to obtain a rank estimator for vertical plane seakeeping performance of combatant monohulls. This estimator $\hat{R}$ yields a ranking number between 1 (poor seakeeping) and 10 (superior seakeeping) and has the following form:

$$\begin{aligned}\hat{R} = {} & 8.42 + 45.1\, C_{WPf} + 10.1\, C_{WPa} - 378\, T/L \\ & + 1.27\, C/L - 23.5\, C_{VPf} - 15.9\, C_{VPa}\end{aligned} \qquad [21]$$

Here the waterplane coefficient and the vertical prismatic coefficient are expressed separately for the forward (f) and the aft (a) portions of the hull. Since the objective for superior seakeeping is high $\hat{R}$, high C_{WP} and low C_{VP}, corresponding to V-shaped hulls, can be seen to provide improved vertical plane seakeeping. Note also that added waterplane

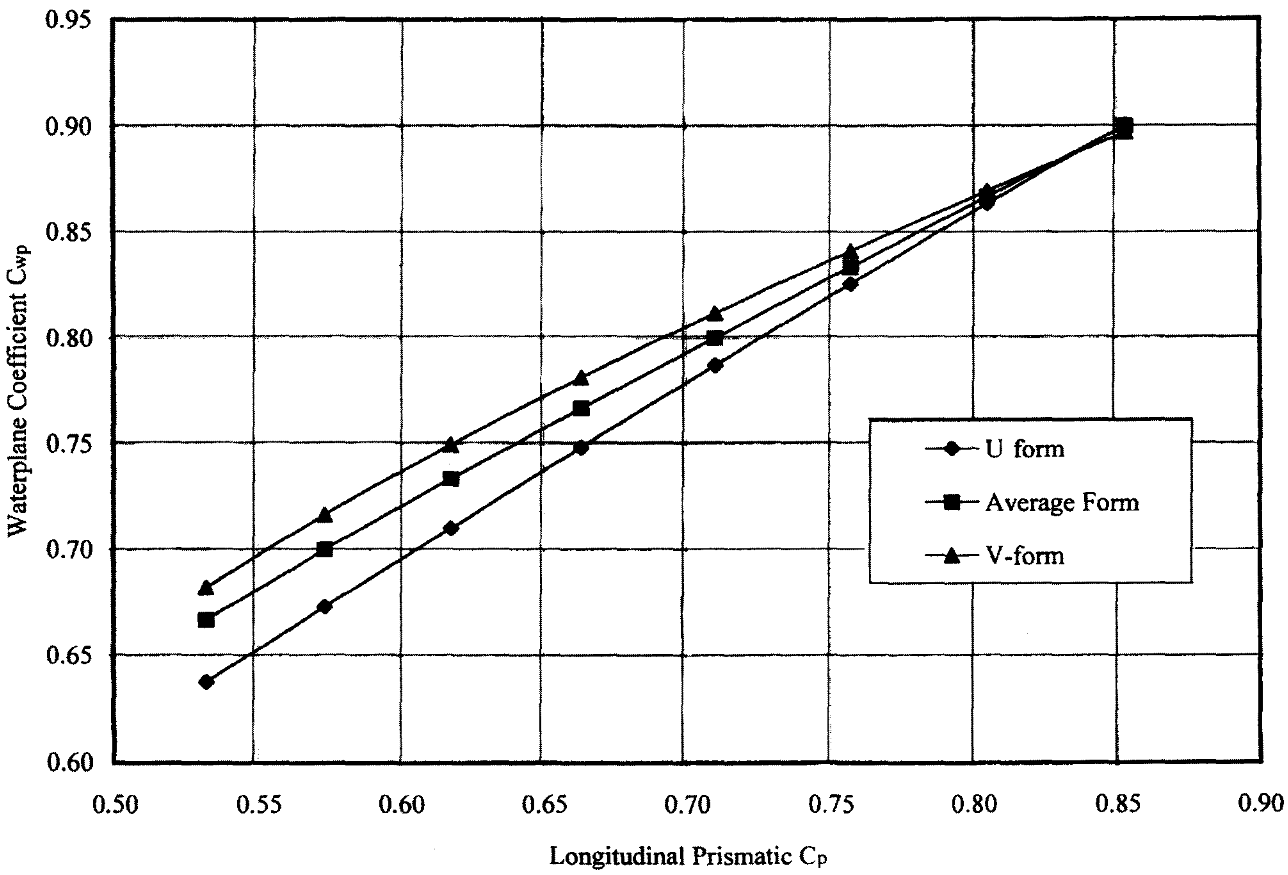


Figure 11.13 Estimates of Waterplane Coefficient C_{WP}—Effect of Hull Form

forward is about 4.5 times as effective as aft and lower vertical prismatic forward is about 1.5 times as effective as aft in increasing $\hat{R}$. Thus, V-shaped hull sections forward provide the best way to achieve greater wave damping in heave and pitch and improve vertical plane seakeeping. Low draft-length ratio T/L and keeping the hull on the baseline well aft to increase the cut-up-ratio C/L also improve vertical plane seakeeping. Parameter C is the distance aft of the forward perpendicular where the hull begins its rise from the baseline to the stern. This logic guided the shaping of the DDG51 hull that has superior vertical-plane seakeeping performance compared to the earlier DD963 hull form that had essentially been optimized based only upon smooth water resistance.

11.2.7 Early Estimates of Hydrostatic Properties

The hydrostatic properties KB and BM_T are needed early in the parametric design process to assess the adequacy of the transverse GM_T relative to design requirements using equation 7.

11.2.7.1 Vertical center of buoyancy KB

An extreme U-shaped hull would have C_{VP} near 1.0 and a KB near 0.5(T); an extreme V-shaped hull would be triangular with C_{VP} near 0.5 and a KB near .667(T). Thus, there is a strong inverse correlation between KB and C_{VP} and C_{VP} can be used to make effective estimates of the vertical center of buoyancy until actual hull offsets are available for hydrostatic analysis.

Two useful theoretical results have been derived for the KB as a function of C_{VP} for idealized hulls with uniform hull sections described by straight sections and a hard chine and by an exponential half breadth distribution with draft, respectively. These results are useful for early estimates for actual hull forms. The first approach yields Moorish's (also Normand's) formula:

$$KB / T = (2.5 - C_{VP})/3 \qquad [22]$$

which is recommended only for hulls with $C_M \leq 0.9$. The second approach yields a formula attributed to both Posdunine and Lackenby:

$$KB / T = (1 + C_{VP})^{-1} \qquad [23]$$

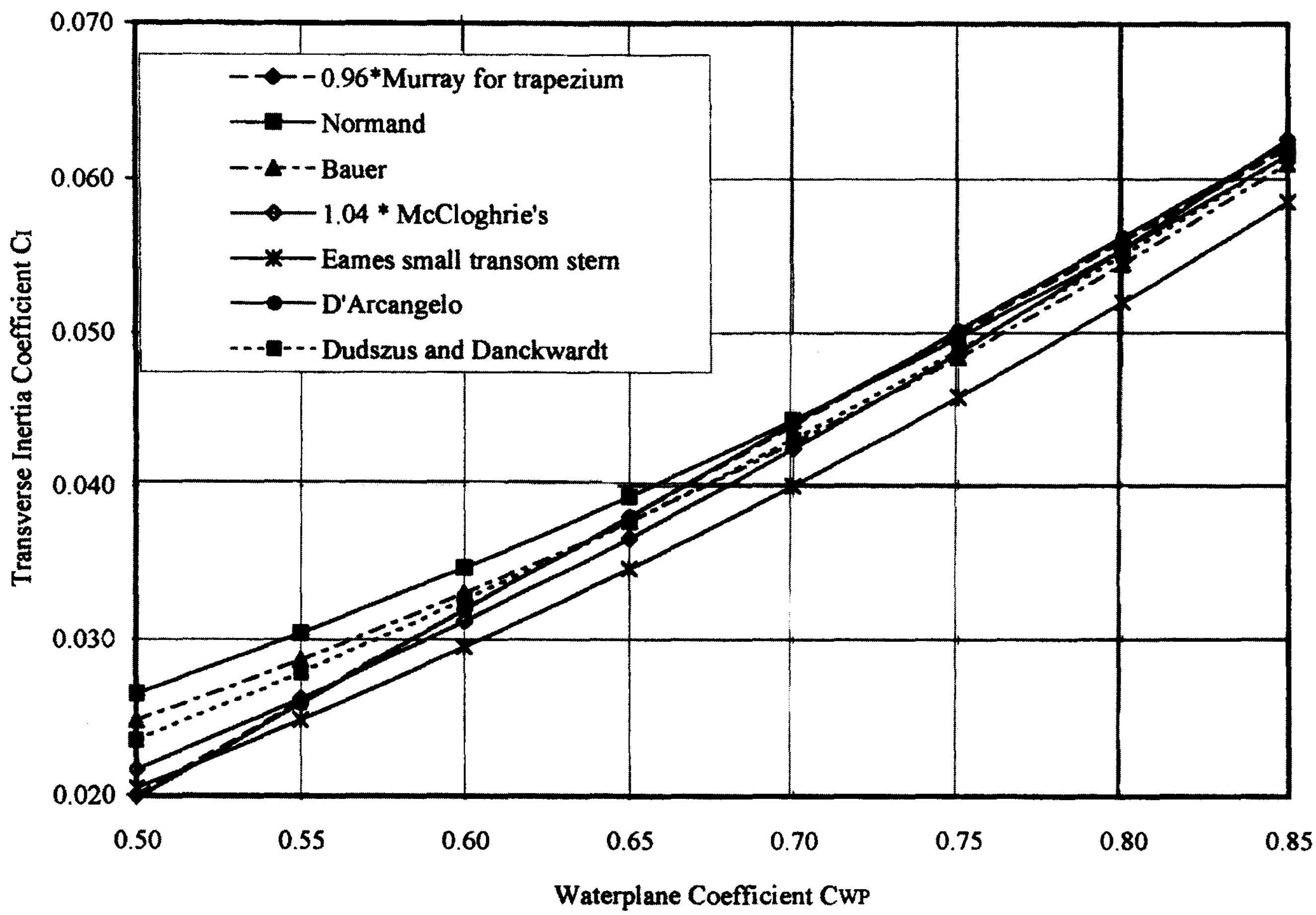


Figure 11.14 Estimates of Transverse Inertial Coefficient C_I

This second approximation is recommended for hulls with $0.9 < C_M$. Posdunine's equation is, thus, recommended for typical larger commercial vessels.

Schneekluth and Bertram (17) also present three regression equations attributed to Normand, Schneekluth, and Wobig, respectively:

$$KB/T = (0.90 - 0.36\, C_M) \qquad [24]$$

$$KB/T = (0.90 - 0.30\, C_M - 0.10\, C_B) \qquad [25]$$

$$KB/T = 0.78 - 0.285\, C_{VP} \qquad [26]$$

11.2.7.2 Location of the metacenters

The dimensions and shape of the waterplane determine the moments of inertia of the waterplane relative to a ship's longitudinal axis I_T and transverse axis I_L. These can be used to obtain the vertical location of the respective metacenters relative to the center of buoyancy using the theoretical results:

$$BM_T = I_T/\nabla \qquad [27]$$

$$BM_L = I_L/\nabla \qquad [28]$$

In early design, the moments of inertia of the waterplane can be effectively estimated using nondimensional inertia coefficients that can be estimated using the waterplane coefficient. Recalling that the moment of inertia of a rectangular section is $bh^3/12$, it is consistent to define nondimensional waterplane inertia coefficients as follows:

$$C_I = I_T/LB^3 \qquad [29]$$

$$C_{IL} = I_L/BL^3 \qquad [30]$$

There is a catalog of models in the literature that allow estimation of C_I and C_{IL} from C_{WP}. These models are summarized in Table 11.VI. The next to last C_I equation represents a 4% increase on McCloghrie's formula that can be shown to be exact for diamond, triangular, and rectangular waterplanes. The seven models for C_I are plotted in Figure 11.14 for comparison. Note that some authors choose to normalize the inertia by the equivalent rectangle value including the constant 12 and the resulting nondimensional coefficients are an order of magnitude higher (a factor of

TABLE 11.VI Equations for Estimating Waterplane Inertia Coefficients

Equations	*Applicability/Source*
$C_I = 0.1216\ C_{WP} - 0.0410$	D'Arcangel0 transverse
$C_{IL} = 0.350\ C_{WP}^2\ 0.405\ C_{WP} + 0.146$	D'Arcangelo longitudinal
$C_I = 0.0727\ C_{WP}^2 + 0.0106\ C_{WP} - 0.003$	Eames, small transom stem (2)
$C_I = 0.04\ (3\ C_{WP} - 1)$	Murray, for trapezium reduced 4% (17)
$C_I = (0.096 + 0.89\ C_{WP}^2)/12$	Normand (17)
$C_I = (0.0372\ (2\ C_{WP} + 1)^3)/12$	Bauer (17)
$C_I = 1.04\ C_{WP}^2/12$	McCloghrie +4% (17)
$C_I = (0.13\ C_{WP} + 0.87\ C_{Wl})/12$	Dudszus and Danckwardt (17)

12). It is, therefore, useful when using other estimates to check for this possibility by comparing the numerical results with one of the estimates in Table 11.VI to ensure that the correct non-dimensionalization is being used.

11.2.8 Target Value for Longitudinal Center of Buoyancy LCB

The longitudinal center of buoyancy LCB affects the resistance and trim of the vessel. Initial estimates are needed as input to some resistance estimating algorithms. Likewise, initial checks of vessel trim require a sound LCB estimate. The LCB can change as the design evolves to accommodate cargo, achieve trim, etc., but an initial starting point is needed. In general, LCB will move aft with ship design speed and Froude number. At low Froude number, the bow can be fairly blunt with cylindrical or elliptical bows utilized on slow vessels. On these vessels it is necessary to fair the stern to achieve effective flow into the propeller, so the run is more tapered (horizontally or vertically in a buttock flow stern) than the bow resulting in an LCB which is forward of amidships. As the vessel becomes faster for its length, the bow must be faired to achieve acceptable wave resistance, resulting in a movement of the LCB aft through amidships. At even higher speeds the bow must be faired even more resulting in an LCB aft of amidships. This physical argument is based primarily upon smooth water powering, but captures the primary influence.

The design literature provides useful guidance for the initial LCB position. Benford analyzed Series 60 resistance data to produce a design lane for the acceptable range of LCB as a function of the longitudinal prismatic. Figure 11.15 shows Benford's *acceptable* and *marginal* ranges for LCB as a percent of ship length forward and aft of amidships, based upon Series 60 smooth water powering results. This reflects the correlation of Cp with Froude number Fn. This exhibits the characteristic form: forward for low Froude numbers, amidships for moderate Froude number ($C_P \approx 0.65$, $F_n \approx 0.25$), and then aft for higher Froude numbers. Note that this *acceptable* range is about 3% ship length wide indicating that the designer has reasonable freedom to adjust LCB as needed by the design as it proceeds without a significant impact on resistance.

Harvald includes a recommendation for the *best possible* LCB as a percent of ship length, plus forward of amidships, in his treatise on ship resistance and propulsion (31):

$$LCB = 9.70 - 45.0\ F_n \pm 0.8 \qquad [31]$$

This band at 1.6% L wide is somewhat more restrictive than Benford's *acceptable* range. Schneekluth and Bertram (17) note two similar recent Japanese results for recommended LCB position as a per cent of ship length, plus forward of amidships:

$$LCB = 8.80 - 38.9\ F_n \qquad [32]$$

$$LCB = -13.5 + 19.4\ C_P \qquad [33]$$

Equation 33 is from an analysis oftankers and bulk carriers and is shown in Figure 11.15 for comparison. It may be linear in longitudinal prismatic simply because a linear regression of LCB data was used in this study.

Watson (18) provides recommendations for the range of LCB *in which it is possible to develop lines with resistance within* 1% *of optimum.* This presentation in similar to

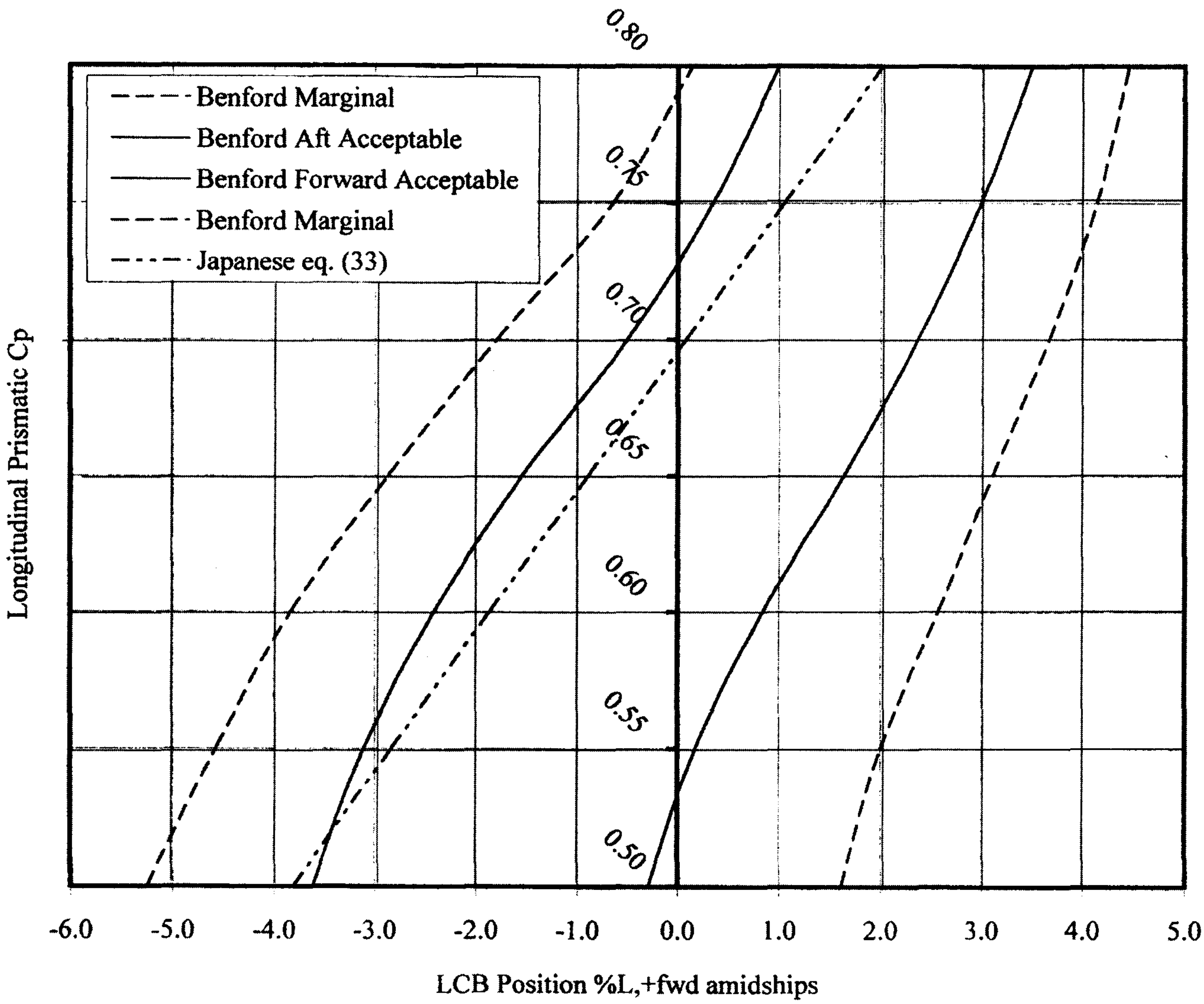


Figure 11.15 Benford's Recommended Design Lane for Longitudinal Center of Buoyancy LCB

Benford's but uses C_B, which also correlates with Froude number Pn, as the independent variable. Watson's recommendation is shown in Figure 11.16. Since a bulbous bow will move the LCB forward, Watson shows ranges for both a bulbous bow and a *normal* bow. This recommendation also exhibits the expected general character. The design lane is about 1.5% L wide when the LCB is near amidships and reduces to below 1.0% for lower and higher speed vessels. Jensen's (29) recommendation for LCB position based upon recent best practice in Germany is also shown in Figure 11.16.

Schneekluth and Bertram (17) note that these LCB recommendations are based primarily on resistance minimization, while propulsion (delivered power) minimization results in a LCB somewhat further aft. Note also that these recommendations are with respect to length between perpendiculars and its midpoint amidships. Using these recommendations with LWL that is typically longer than LBP and using its midpoint, as amidships, which is convenient in earliest design, will result in a position further aft relative to length between perpendiculars, thus, approaching the power minimization location.

11.3 PARAMETRIC WEIGHT AND CENTERS ESTIMATION

To carry out the iteration on the ship dimensions and parameters needed to achieve a balance between weight and displacement and/or between required and available hull volume, deck area, and/or deck length, parametric models are needed for the various weight and volume requirements.

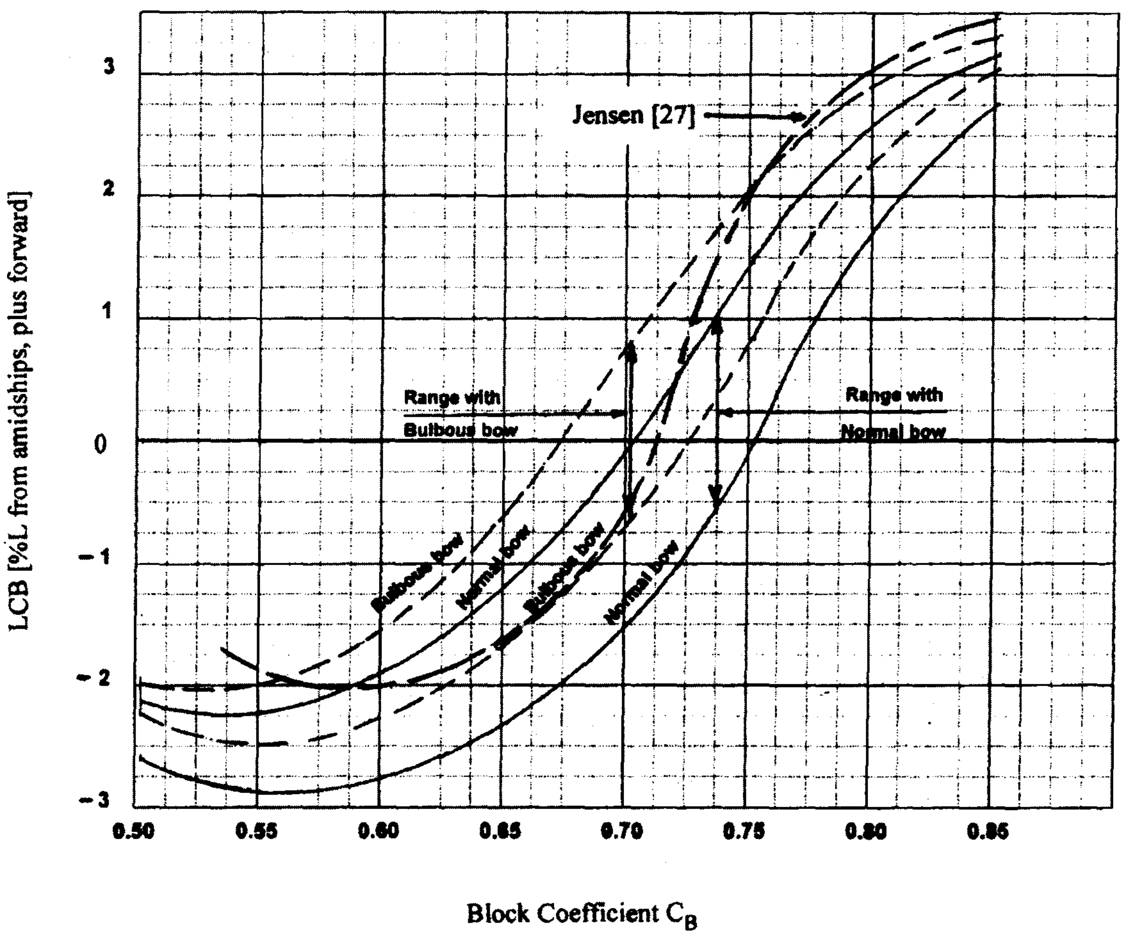


Figure 11.16 Watson's (18) and Jensen's (28) Recommended Longitudinal Center of Buoyancy LCB

Some of this information is available from vendor's information as engines and other equipment are selected or from characteristics of discrete cargo and specified payload equipment. In this Section, parametric models will be illustrated for the weight components and their centers for commercial vessels following primarily the modeling of Watson and Gilfillan (1) and Watson (18). It is not a feasible goal here to be comprehensive. The goal is to illustrate the approach used to model weights and centers and to illustrate the balancing of weight and displacement at the parametric stage of a larger commercial vessel design. See Watson (18) and Schneekluth and Bertram (17) for additional parametric weight and volume models.

11.3.1 Weight Classification

The data gathering, reporting, and analysis of ship weights are facilitated by standard weight classification. The Maritime Administration has defined the typical commercial ship design practice; U.S. Navy practice uses the Extended Ship Work Breakdown Structure (ESWBS) defined in (32). The total displacement in commercial ships is usually divided into the Lightship weight and the Total Deadweight, which consists of the cargo and other variable loads.

The U.S. Navy ship breakdown includes seven *one-digit* weight groups consisting of:

Group 1 Hull Structure
Group 2 Propulsion Plant
Group 3 Electric Plant
Group 4 Command and Surveillance
Group 5 Auxiliary Systems
Group 6 Outfit and Furnishings
Group 7 Armament

U.S. Navy design practice, as set forth in the Ship Space Classification System (SSCS), also includes five *one-digit* area/volume groups consisting of:

Group 1 Military Mission
Group 2 Human Support

Group 3 Ship Support
Group 4 Ship Machinery
Group 5 Unassigned

In small boat designs, a weight classification system similar to the navy groups is often followed. The total displacement is then as follows depending upon the weight classification system used:

$$\Delta = W_{LS} + DWT_T = \sum_{i=1}^{m} W_i + \sum_{j=1}^{n} loads_j + W_{margin} + W_{growth} \qquad [32]$$

Focusing on the large commercial vessel classification system as the primary example here, the Lightship weight reflects the vessel ready to go to sea without cargo and loads and this is further partitioned into:

$$W_{LS} = W_S + W_M + W_o + W_{margin} \qquad [33]$$

where:

W_S = the structural weight
W_M = propulsion machinery weight
W_o = outfit and hull engineering weight
W_{margin} = Lightship design (or Acquisition) weight margin that is included as protection against the underprediction of the required displacement.

In military vessels, future growth in weight and KG is expected as weapon systems and sensors (and other mission systems) evolve so an explicit future growth or Service Life Allowance (SLA) weight margin is also included as W_{growth}.

The total deadweight is further partitioned into:

$$DWT_T = DWT_C + W_{FO} + W_{LO} + W_{FW} + W_{C\&E} + W_{PR} \qquad [34]$$

where:

DWT_C = cargo deadweight
W_{FO} = fuel oil weight
W_{LO} = lube oil weight
W_{FW} = fresh water weight
$W_{C\&E}$ = weight of the crew and their effects
W_{PR} = weight of the provisions.

11.3.2 Weight Estimation

The estimation of weight at the early parametric stage of design typically involves the use of parametric models that are developed from weight information for similar vessels. A fundamental part of this modeling task is the selection of relevant independent variables that are correlated with the weight or center to be estimated. The literature can reveal effective variables or first principles can be used to establish candidate variables. For example, the structural weight of a vessel could vary as the volume of the vessel as represented by the Cubic Number. Thus, many weight models use CN = LBDIl 00 as the independent variable. However, because ships are actually composed of stiffened plate surfaces, some type of area variable would be expected to provide a better correlation. Thus, other weight models use the area variable L(B + D) as their independent variable. Section 11.5 below will further illustrate model development using multiple linear regression analysis. The independent variables used to scale weights from similar naval vessels were presented for each *three digit* weight group by Straubinger et al (33).

11.3.2.1 Structural weight

The structural weight includes (1) the weight of the basic hull to its depth amidships; (2) the weight of the superstructures, those full width extensions of the hull above the basic depth amidships such as a raised forecastle or poop; and (3) the weight of the deckhouses, those less than full width erections on the hull and superstructure. Because the superstructures and deckhouses have an important effect on the overall structural VCG and LCG, it is important to capture the designer's intent relative to the existence and location of superstructures and deckhouses as early as possible in the design process.

Watson and Gilfillan proposed an effective modeling approach using a specific modification of the Lloyd's Equipment Numeral E as the independent variable (1):

$$E = E_{hull} + E_{SS} + E_{dh} = L(B + T) + 0.85L(D - T) + 0.85 \sum_i \ell_i h_i + 0.75 \sum_j \ell_j h_j \qquad [35]$$

This independent variable is an area type independent variable. The first term represents the area of the bottom, the equally heavy main deck, and the two sides below the waterline. (The required factor of two is absorbed into the constant in the eventual equation.) The second term represents the two sides above the waterline, which are somewhat (0.85) lighter since they do not experience hydrostatic loading. These first two terms are the hull contribution EhullThe third term is the sum of the profile areas (length x height) of all of the superstructure elements and captures the superstructure contribution to the structural weight. The fourth term is the sum of the profile area of all of the deckhouse elements, which are relatively lighter (0.75/0.85) because they are further from wave loads and are less than full width.

Watson and Gilfillan (I) found that if they scaled the structural weight data for a wide variety of large steel commercial vessels to that for a standard block coefficient at 80% of depth $C_B' = 0.70$, the data reduced to an acceptably tight band allowing its regression relative to E as follows:

$$W_S = W_S(E) = K\,E^{1.36}\,[1 + 0.5(C_B' - 0.70)] \qquad [36]$$

The term in the brackets is the correction when the block coefficient at 80% of depth C_B' is other than 0.70. Since most designers do not know C_B' in the early parameter stage of design, it can be estimated in terms of the more commonly available parameters by:

$$C_B' = C_B + (1 - C_B)[(0.8D - T)/3T] \qquad [37]$$

Watson and Gilfillan found that the 1.36 power in equation 36 was the same for all ship types, but that the constant K varied with ship type as shown in Table 11.VII.

This estimation is for 100% mild steel construction. Watson (18) notes that this scheme provides estimates that are *a little high today.*

This structural weight-modeling scheme allows early estimation and separate location of the superstructure and deckhouse weights, since they are included as explicit contributions to E. The weight estimate for a single deckhouse can be estimated using the following approach:

$$W_{dh} = W_S(E_{hull} + E_{SS} + E_{dh}) - W_S(E_{hull} + E_{SS}) \qquad [38]$$

Note that the deckhouse weight cannot be estimated accurately using Wdh(Edh) because of the nonlinear nature of this model. If there are two deckhouses, a similar approach can be used by removing one deckhouse at a time from E.

A comparable approach would directly estimate the unit area weights of all surfaces of the deckhouse; for example, deckhouse front 0.10 t/m^2; deckhouse sides, top and back 0.08 t/m^2; decks inside deckhouse 0.05 t/m^2; engine casing 0.07 t/m^2, and build up the total weight from first principles.

Parallel to equation 38, the weight estimate for a single superstructure can be estimated using:

$$W_{SS} = W_S(E_{hull} + E_{SS}) - W_S(E_{hull}) \qquad [39]$$

These early weight estimates for deckhouse and superstructure allow them to be included with their intended positions (LCG and VCG) as early as possible in the design process.

TABLE 11.VII Structural Weight Coefficient K (1, 18)

Ship type	*K mean*	*K range*	*Range of E*
Tankers	0.032	±0.003	1500 < E < 40 000
Chemical tankers	0.036	±0.001	1900 < E < 2500
Bulk carriers	0.031	±0.002	3000 < E < 15 000
Container ships	0.036	±0.003	6000 < E < 13 000
Cargo	0.033	±0.004	2000 < E < 7000
Refrigerator ships	0.034	±0.002	4000 < E < 6000
Coasters	0.030	±0.002	1000 < E < 2000
Offshore supply	0.045	±0.005	800 < E < 1300
Tugs	0.044	±0.002	350 < E < 450
Fishing trawlers	0.041	±0.001	250 < E < 1300
Research vessels	0.045	±0.002	1350 < E < 1500
RO-RO ferries	0.031	±0.006	2000 < E < 5000
Passenger ships	0.038	±0.001	5000 < E < 15 000
Frigates/corvettes	0.023		

11.3.2.2 Machinery weight

First, note that the machinery weight in the commercial classification includes only the propulsion machinery—primarily the prime mover, reduction gear, shafting, and propeller. Watson and Gilfillan proposed a useful separation of this weight between the main engine(s) and the remainder of the machinery weight (1):

$$W_M = W_{ME} + W_{rem} \qquad [40]$$

This approach is useful because in commercial design, it is usually possible to select the main engine early in the design process permitting the use of specific vendor's weight and dimension information for the prime mover from very early in the design. If an engine has not been selected, they provided the following conservative regression equation for an estimate about 5% above the mean of the 1977 diesel engine data:

$$W_{ME} = \sum_i 12.0\,(MCR_i/N_{ei})^{0.84} \qquad [41]$$

where i is the index on multiple engines each with a Maximum Continuous Rating MCR_i (kW) and engine rpm N_{ei}. The weight of the remainder of the machinery varies as the total plant MCR as follows:

$$W_{rem} = C_m\,(MCR)^{0.70} \qquad [42]$$

where:

C_m = 0.69 bulk carriers, cargo vessels, and container ships
= 0.72 for tankers
= 0.83 for passenger vessels and ferries
= 0.19 for frigates and corvettes when the MCR is in kW.

With modern diesel electric plants using a central power station concept, Watson (18) suggests that the total machinery weight equation 40 can be replaced by:

$$W_M = 0.72\ (MCR)^{0.78} \qquad [43]$$

where now MCR is the total capacity of all generators in kW. These electric drive machinery weight estimates take special care since the outfit weight included below traditionally includes the ship service electrical system weights.

11.3.2.3 Outfit weight

The outfit includes the remainder of the Lightship weight. In earlier years, these weights were classified into two groups as *outfit*, which included electrical plant, other distributive auxiliary systems such as HVAC, joiner work, furniture, electronics, paint, etc., and *hull engineering*, which included the bits, chocks, hatch covers, cranes, windlasses, winches, etc. Design experience revealed that these two groups varied in a similar manner and the two groups have been combined today into the single group called Outfit. Watson and Gilfillan estimate these weights using the simple model (1):

$$W_o = C_o\ LB \qquad [44]$$

where the outfit weight coefficient C_o is a function of ship type and for some ship types also ship length as shown in Figure 11.17.

11.3.2.4 Deadweight items

The cargo deadweight is usually an owner's requirement or it can be estimated from an analysis of the capacity of the hull. The remaining deadweight items can be estimated from first principles and early decisions about the design of the vessel.

The selection of machinery type and prime mover permits the estimation of the Specific Fuel Rate (SFR) (t/kWhr) for the propulsion plant so that the fuel weight can be estimated using:

$$W_{FO} = SFR \times MCR \times range/speed \times margin \qquad [45]$$

Early general data for fuel rates can be found in the SNAME Technical and Research Bulletins #3-11 for steam plants (34), #3-27 for diesel plants (35) and #3-28 for gas turbine plants (36). For diesel engines, the SFR can be taken as the vendor's published test bed data with 10% added for shipboard operations producing a value of about 0.000190 t/kWhr for a large diesel today. Second generation gas turbines might have a SFR of about 0.000215 t/kWhr.

In equation 45, the margin is for the fuel tankage that can be an overall percentage such as 5% or it might be 10%

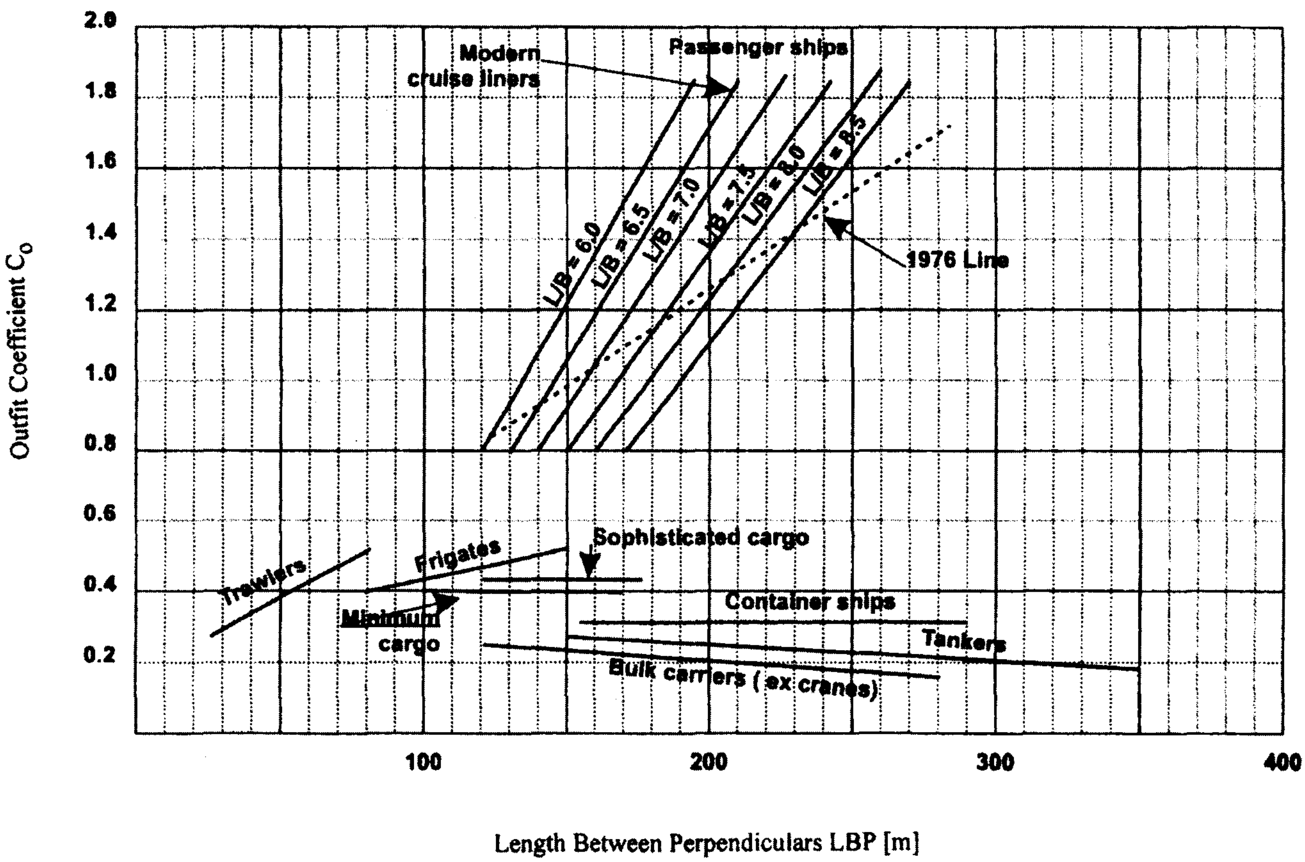


Figure 11.17 Outfit Weight Coefficient C_o (18)

for just the final leg of a multi-leg voyage. Overall this estimate is conservative, because the vessel may not require full MCR except in the worst service conditions and there are margins both in the SFR and on the overall capacity. This conservatism can cover generator fuel that can be estimated separately in a similar manner as the design evolves.

The lube oil weight can be taken from practice on similar vessels. This usually depends upon the type of main machinery. Overall recommendations (37) include:

$$W_{LO} = 20 \text{ t, medium speed diesel(s)} \\ = 15 \text{ t, low speed diesel} \qquad [46]$$

As an alternative, an approach like equation 45 can be used with the vendor's specific lube oil consumption data with tankage provided for the total consumption in about 50 voyages.

The weight of fresh water depends upon the designer's intent relative to onboard distillation and storage. Modern commercial vessels often just carry water for the entire voyage and eliminate the need to operate and maintain water-making equipment with a small crew. Naval vessels and cruise vessels obviously have much higher capacity demands making onboard distillation more of a necessity. On the basis of using 45 gallons per person per day, the total water tankage weight would need to be:

$$W_{FW} = 0.17 \text{ t/(person} \times \text{day)} \qquad [47]$$

with perhaps 10 days storage provided with onboard distillation and 45 days provided without onboard distillation.

The weight of the crew and their effects can be estimated as:

$$W_{C\&E} = 0.17 \text{ t/person} \qquad [48]$$

for a commercial vessel's crew and extranumeraries, while a naval vessel might use 0.18 t/person for officers and 0.104 t/person for enlisted (33).

The provisions and stores weight can be estimated as:

$$W_{PR} = 0.01 \text{ t/(person} \times \text{day)} \qquad [49]$$

for the provisions, stores, and their packaging. Naval vessel standards provide about 40 gallons water per person or accommodation per day and provisions and stores at about 0.0036 t/(person × day) (33).

11.3.3 Centers Estimation

The estimation of centers of the various weight groups early in the design process can use parametric models from the literature and reference to a preliminary inboard profile, which reflects the early design intent for the overall arrangements. The structural weight can be separated into the basic hull and the superstructure and deckhouse weights using equations 38 and 39. The VCG of the basic hull can be estimated using an equation proposed by Kupras (38):

$$\begin{aligned} VCG_{hull} &= 0.01D\,[46.6 + 0.135(0.81 - C_B)(L/D)^2] \\ &\quad + 0.008D(L/B - 6.5),\ L \le 120 \text{ m} \\ &= 0.01D\,[46.6 + 0.135(0.81 - C_B)(L/D)^2], \\ &\quad 120 \text{ m} < L \end{aligned} \qquad [50]$$

The longitudinal position of the basic hull weight will typically be slightly aft of the LCB position. Watson (18) gives the suggestion:

$$LCG_{hull} = -0.15 + LCB \qquad [51]$$

where both LCG and LCB are in percent ship length, plus forward of amidships.

The vertical center of the machinery weight will depend upon the innerbottom height h_{bd} and the height of the overhead of the engine room D´. With these known, Kupras (38) notes that the VCG of the machinery weight can be estimated as:

$$VCG_M = h_{db} + 0.35(D' - h_{db}) \qquad [52]$$

which places the machinery VCG at 35% of the height within the engine room space. This type of simple logic can be adapted for the specific design intent in a particular situation. In order to estimate the height of the innerbottom, minimum values from classification and Coast Guard requirements can be consulted giving for example:

$$h_{db} \ge 32B + 190\sqrt{T} \text{ (mm) (ABS)}$$

or

$$h_{db} \ge 45.7 + 0.417L \text{ (cm) (46CFR171.105)}$$

The innerbottom height might be made greater than indicated by these minimum requirements in order to provide greater doublebottom tank capacity, meet double hull requirements, or to allow easier structural inspection and tank maintenance.

The longitudinal center of the machinery weight depends upon the overall layout of the vessel. For machinery aft vessels, the LCG can be taken near the after end of the main engines. With relatively lighter prime movers and longer shafting, the relative position of this center will move further aft. Lamb (14) proposed a scheme that separated the weights and centers of the engines, shafting, and propeller at the earliest stage of design in order to develop an aggregate center for W_M.

The vertical center of the outfit weight is typically above the main deck and can be estimated using an equation proposed by Kupras (38):

$$
\begin{aligned}
VCG_o &= O + 1.25, & L \leq 125 \text{ m} \\
&= O + 1.25 + 0.01(L-125), & 125 < L \leq 250 \text{ m} \quad [53] \\
&= O + 2.50, & 250 \text{ m} < L
\end{aligned}
$$

The longitudinal center of the outfit weight depends upon the location of the machinery and the deckhouse since significant portions of the outfit are in those locations. The remainder of the outfit weight is distributed along the entire hull. Lamb (14) proposed a useful approach to estimate the outfit LCG that captures elements of the design intent very early in the design process. Lamb proposed that the longitudinal center of the machinery LCG_M be used for a percentage of W_o, the longitudinal center of the deckhouse LCG_{dh} be used for a percentage of W_o, and then the remainder of W_o be placed at amidships. Adapting the original percentages proposed by Lamb to a combined outfit and hull engineering weight category, this yields approximately:

$$
\begin{aligned}
LCG_o = (&25\%\ W_o \text{ at } LCG_M,\ 37.5\% \text{ at } LCG_{dh}, \\
&\text{and } 37.5\% \text{ at amidships}) \qquad [54]
\end{aligned}
$$

The specific fractions can be adapted based upon data for similar ships. This approach captures the influence of the machinery and deckhouse locations on the associated outfit weight at the earliest stages of the design.

The centers of the deadweight items can be estimated based upon the preliminary inboard profile arrangement and the intent of the designer.

11.3.4 Weight Margins

Selecting margins, whether on power, weight, KG, chilled water, space, or many other quantities, is a matter of important design philosophy and policy. If a margin is too small, the design may fail to meet design requirements. If a margin is too large, the vessel will be overdesigned resulting in waste and potentially the designer's failure to be awarded the project or contract. There is a multiplier effect on weight and most other ship design characteristics: for example, adding one tonne of weight will make the entire vessel more than one tonne heavier since the hull structure, machinery, etc. must be enlarged to accommodate that added weight. Most current contracts include penalty clauses that enter effect if the vessel does not make design speed or some other important attribute.

A typical commercial vessel Lightship design (or acquisition) weight margin might be 3-5%; Watson and Gilfillan (1) recommend using 3% when using their weight estimation models. This is usually placed at the center of the rest of the Lightship weight. This margin is included to protect the design (and the designer) since the estimates are being made very early in the design process using approximate methods based only upon the overall dimensions and parameters of the design.

Standard U.S. Navy weight margins have been developed from a careful statistical analysis of past designlbuild experience (39) following many serious problems with overweight designs, particularly small vessels which were delivered overweight and, thus, could not make speed. These studies quantified the acquisition margin needed to cover increases experienced during preliminary design, contract design, construction, contract modifications, and delivery of Government Furnished Material.

Military ships also include a future growth margin or Service Life Allowance on weight, KG, ship service electrical capacity, chilled water, etc. since the development and deployment of improved sensors, weapons, and other mission systems typically results in the need for these margins during upgrades over the life of the vessel. It is sound design practice to include these margins in initial design so that future upgrades are feasible with acceptable impact. Future growth margin policies vary with country. Watson (18) suggests 0.5% per year of expected ship life. Future growth margins are typically not included in commercial designs since they are developed for a single, specific purpose. Typical U.S. Navy total weight and KG margins are shown in Table 11.VIII.

TABLE 11.VIII U.S. Naval Weight and KG Margins (39)

Acquisition Margins (on Lightship Condition)

Total Design Weight Margin, mean	5.9%
Total Design Weight Margin, mean plus one Standard Deviation	17.0%
Total Design KG Margin, mean	4.8%
Total Design KG Margin, mean plus one Standard Deviation	13.5%

Service Life Allowances (on Full Load Departure)

VESSEL TYPE	WEIGHT MARGIN	KG MARGIN
Carriers	7.5%	0.76m
Other combatants	10.0%	0.30 m
Auxiliary ships	5.0%	0.15 m
Special ships and craft	5.0%	0.15 m
Amphibious warfare vessels		
Large deck	7.5%	0.76m
Other	5.0%	0.30 m

11.3.5 Summation and Balancing Using Spreadsheets

The summation of weights and the determination of the initial transverse metacentric height GMT and trim, are key to the initial sizing and preliminary arrangement of any vessel. This task can be effectively accomplished using any number of computer tools. Within the teaching of ship design at the University of Michigan extensive use is made of spreadsheets for this purpose. By their automatic recalculation when any input parameter is changed, spreadsheets are valuable interactive design tools since they readily support trade-off and iterative design studies.

The WEIGHTS I spreadsheet for Parametric Stage Weight Summation is shown on the left in Figure 11.18 as an illustration. This spreadsheet is used to the support design iteration needed to achieve a balance between weight and displacement, determine an acceptable initial GMT' and establish the initial trim. At this stage the longitudinal center of flotation (LCF) is usually not estimated so the trim is not resolved into draft forward TF and draft aft T_A. The WEIGHTS I spreadsheet supports the inclusion of a design Lightship weight margin, free surface margin FS in percent, and a design KGmarginThe weights and centers are processed to obtain the total VCG and total LCG. The design KG used to establish GMT is then obtained using:

$$KG_{design} = VCG(1 + FS/100) + KG_{margin} \qquad [55]$$

The designer can iterate on the initial estimates of the dimensions and block coefficient C_B. At this stage of design, the hydrostatic properties, BM_T, KB, BM_L, and LCB are selected or estimated using parametric equations as presented in Section 11.2. The trim is obtained from the total LCG using:

$$trim = T_A - T_F = (LCG - LCB)L/GM_L \qquad [56]$$

To facilitate early design studies, the weights and centers estimation methods outlined in this Section are implemented on the linked Weights and Centers Estimation for Weight I spreadsheet shown on the right in Figure 11.18. The resulting weights and centers are linked directly to the italicized weights and centers entries in the WEIGHTS I spreadsheet summary. Inputs needed for these design models are entered on the linked Weights and Centers Estimation spreadsheet.

11.4 HYDRODYNAMIC PERFORMANCE ESTIMATION

The conceptual design of a vessel must utilize physics-based methods to simulate the propulsion, maneuvering, and seakeeping hydrodynamic performance of the evolving design based only upon the dimensions, parameters, and intended features of the design. An early estimate of resistance is needed in order to establish the machinery and engin~room size and weight, which will directly influence the required overall size of the vessel. Maneuvering and seakeeping should also be checked at this stage of many designs since the evolving hull dimensions and parameters will affect this performance and, thus, the maneuvering and seakeeping requirements may influence their selection. This Section will illustrate this approach through public domain teaching and design software that can be used to carry out these tasks for displacement hulls. This Windows software environment is documented in Parsons et al (40). This documentation and the compiled software are available for download at the following URL: *www-personal.engin.umich.edu/-parsons*

11.4.1 Propulsion Performance Estimation

11.4.1.1 Power and efficiency definitions

The determination of the required propulsion power and engine sizing requires working from a hull total tow rope resistance prediction to the required installed prime mover brake power. It is important to briefly review the definitions used in this work (41).

The approach used today has evolved from the tradition of initially testing a hull or a series of hulls without a propeller, testing an individual or series of propellers without a hull, and then linking the two together through the definition of hull-propeller interaction factors. The various powers and efficiencies of interest are shown schematically in Figure 11.19. The hull without a propeller behind it will have a total resistance R_T at a speed V that can be expressed as the effective power P_E:

$$P_E = R_T V/1000 \text{ (kW)} \qquad [57]$$

where the resistance is in Newtons and the speed is in m/s. The open water test of a propeller without a hull in front of it will produce a thrust T at a speed V_A with an open water propeller efficiency η_o and this can be expressed as the thrust power P_T:

$$P_T = TV_A/1000 \text{ (kW)} \qquad [58]$$

These results for the hull without the propeller and for the propeller without the hull can be linked together by the definition of the hull-propeller interaction factors defined in the following:

$$V_A = V(1 - w) \qquad [59]$$

$$T = R_T/(1 - t) \qquad [60]$$

$$\eta_P = \eta_o \eta_r \qquad [61]$$

WEIGHTS 1 - PARAMETER STAGE WEIGHT SUMMARY R(11)

Condition: **Full Load Departure**

DESIGN PARAMETERS					
enter data in boxes					
LWL	132.00	meters		Note: weights and centers in *italics* are linked to models on Sheet 1	
B	22.00	meters			
T	6.90	meters			
Cb	0.630				
Weight Margin	3.00	per cent of Light Ship at CG for Light Ship			
(1 + s)	1.005	shell/appendage allowance			
KG Margin	0.30	meters			
Free Surface Margin	3.00	per cent of KG			
BMT	5.90	meters			
KB = VCB	3.50	meters		estimates from prelim.	
BML	170.00	meters		design equations	
LCB	67.00	meters from the FP			
Water Weight Density	1.025	tonnes/m^3		(SW 1.025; FW 1.000)	
WEIGHT CATEGORY	WT	VCG	product	LCG	product
	[t]	[m abv. BL]		[m from FP]	
*Hull Structure	*3111.6*	6.36	19782.8	67.90	211273.2
*Superstructures	*144.8*	14.50	2099.3	15.00	2171.7
*Deckhouses	*107.6*	18.00	1936.1	115.00	12369.3
Total Structure	3364.0				
*Outfit	*1016.4*	*14.32*	14554.8	*96.63*	98209.7
*Special Outfit	0.0	0.00	0.0	0.00	0.0
*Machinery	*449.8*	*5.40*	2426.9	115.00	51731.7
*Permanent Ballast	0.0	0.00	0.0	0.00	0.0
*Light Ship Margin	144.9	8.45	1224.0	77.79	11272.7
Light Ship Weight	4975.1	8.45		77.79	
*Cargo Deadweight	7600.0	8.27	62852.0	59.90	455240.0
*Fuel Oil	*213.8*	7.00	1496.5	18.00	3848.1
*Lube Oil	20.0	10.00	200.0	110.00	2200.0
*Water	*183.6*	10.00	1836.0	110.00	20196.0
*Crew and Effects	*4.1*	16.50	67.3	120.00	489.6
*Provisions	*10.8*	14.00	151.2	120.00	1296.0
*Temporary Ballast	0.0	0.00	0.0	0.00	0.0
Total Deadweight	8032.3	8.29		60.17	
Total Weight	13007.4	8.35	total VCG	66.91	total LCG
Displacement	13004.0	0.03	%; + weight exceeds displacement		
GM AND TRIM RESULTS					
Design KG	8.90	meters, including design and free surface margins			
GMT	0.50	meters			
GML	165.15	meters			
Trim	-0.07	meters; + by the stern			

WEIGHTS AND CENTERS ESTIMATION FOR WEIGHTS 1 (R11)

Models from: Watson, D. G. M. and A. W. Gilfillan, "Some Ship Design Methods," Transactions RINA, 1977.
Kupras, L. K., "Optimization Method and Parametric Study in Precontract Ship Design," International Shipbuilding Progress, May, 1971.
Watson, D. G. M., Practical Ship Design, Elsevier Science Ltd, Oxford, UK, 1998.

Additional Parameters	input			
D	13	meters		
superstructures sum(li*hi)	180	m^2		
deckhouses sum(li*hi)	150	m^2		
structural K	0.0336	from Watson & Gilfillan or Watson Table		
distance from LCB to hull LCG	0.680	% LWL positive aft		
outfit Co	0.35	from Watson & Gilfillan or Watson Figure		
fraction of Wo at machinery	0.25	|		
fraction of Wo at amidships	0.375	| fractions need to total one =		
fraction of Wo at deckhouse	0.375	|		check sum
total propulsion MCR	6500	kW		
number of main engines	2			
propulsion engine Ne	450	rpm		
ship type coeff. for Wrem	0.69	[0.69 cargo; 0.72 tankers; 0.83 pass.;		
fuel capacity margin	5	per cent on total		0.19 frigates]
endurance range	2500	nautical miles		
endurance speed	17	knots		
specific fuel rate	0.000213	t/kW*hr [use vendor data + 10%]		
engineroom overhead	13	meters above baseline		
innerbottom height	1.3	meters above baseline		transfer
complement (crew+extras)	24	people		from
endurance days	45	days		Weights I
			L	132
Structural weight estimate			B	22
Cb'	0.6926		T	6.9
Ehull	4499.2		Cb	0.63
Esuperstructure	153.0		LCB	67
Edeckhouse	112.5			
Ws hull+ss+dh	3364.0	tonnes		
Ws hull+ss	3256.4	tonnes		
Ws hull only	3111.6	tonnes		
Ws superstructure	144.8	tonnes		
Ws deckhouse	107.6	tonnes		
Machinery weight estimate				
Wme	127.8	tonnes <- enter actual weight from vendor's		
Wrem	322.0	tonnes	data when available	
Total Wm	449.8	tonnes		
Wfuel	213.8	tonnes		

Figure 11.18 WEIGHTS I Parametric Stage Weights Summation Spreadsheet

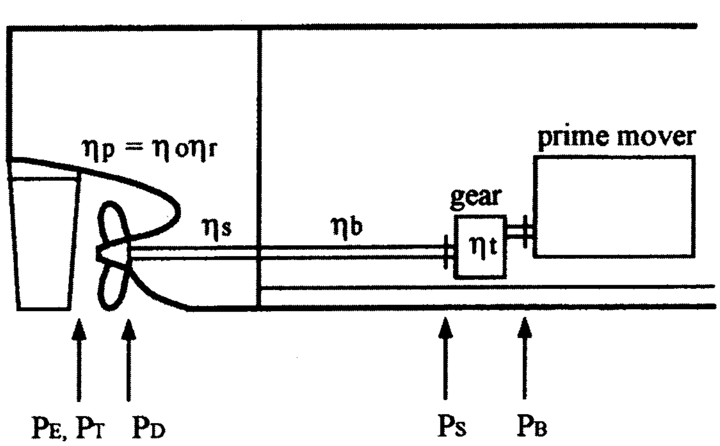


Figure 11.19 Location of Various Power Definitions

where:

w = Taylor wake fraction
t = thrust deduction fraction
η_P = behind the hull condition propeller efficiency
η_r = relative rotative efficiency that adjusts the propeller's open water efficiency to its efficiency behind the hull.

Note that η_r is not a true thermodynamic efficiency and may assume values greater than one.

Substituting equations 59 and 60 into equation 58 and using equation 57 yields the relationship between the thrust power and the effective power:

$$P_T = P_E\,(1 - w)/(1 - t) \qquad [62]$$

from which we define the convenient grouping of terms called the hull efficiency η_h:

$$\eta_h = (1 - t)/(1 - w) = P_E/P_T \qquad [63]$$

The hull efficiency can be viewed as the ratio of the work done on the hull P_E to the work done by the propeller P_T. Note also that η_h is not a true thermodynamic efficiency and may assume values greater than one.

The input power delivered to the propeller P_D is related to the output thrust power from the propeller P_T by the behind the hull efficiency equation 61 giving when we also use equation 63:

$$P_D = P_T / \eta_P = P_T/(\eta_o\eta_r) = P_E/(\eta_h\eta_o\eta_r) \qquad [64]$$

The shaft power P_S is defined at the output of the reduction gear or transmission process, if installed, and the brake power P_B is defined at the output flange of the prime mover.

When steam machinery is purchased, the vendor typically provides the high pressure and low-pressure turbines and the reduction gear as a combined package so steam plant design typically estimates and specifies the shaft power P_S, since this is what steam turbine the steam turbine vendor must provide. When diesel or gas turbine prime movers are used, the gear is usually provided separately so the design typically estimates and specifies the brake power P_B, since this is what prime mover the prime mover vendor must provide. The shaft power P_S is related to the delivered power P_D transmitted to the propeller by the sterntube bearing and seal efficiency η_s and the line shaft bearing efficiency η_b by:

$$P_S = P_D/(\eta_s\eta_b) \qquad [65]$$

The shaft power P_S is related to the required brake power P_B by the transmission efficiency of the reduction gear or electrical transmission process η_t by:

$$P_B = P_S / \eta_t \qquad [66]$$

Combining equations 64, 65, and 66 now yields the needed relationship between the effective power P_E and the brake power at the prime mover P_B:

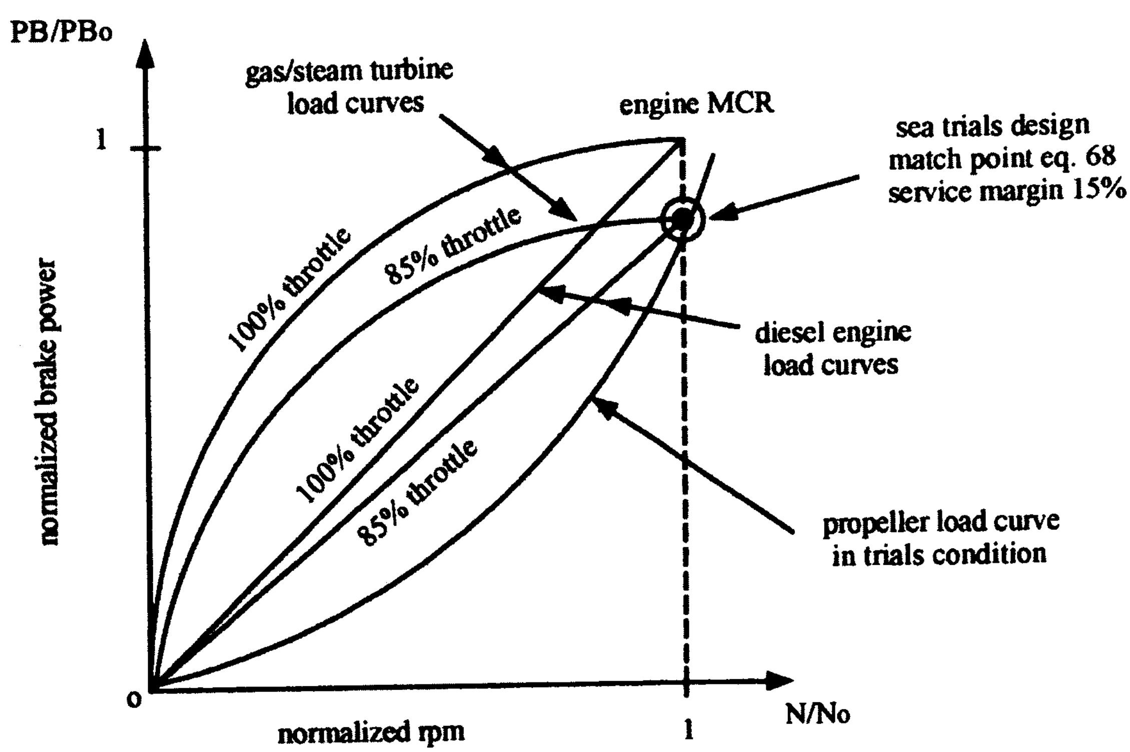


Figure 11.20 Propulsion Trials Propeller Design Match Point

$$P_B = P_E/(\eta_h\eta_o\eta_r\eta_s\eta_b\eta_t) \qquad [67]$$

11.4.1.2 Power margins

In propulsion system design, the design point for the equilibrium between the prime mover and the propulsor is usually the initial sea trials condition with a new vessel, clean hull, calm wind and waves, and deep water. The resistance is estimated for this ideal trials condition. A *power design margin* Mo is included within or applied to the predicted resistance or effective power in recognition that the estimate is being made with approximate methods based upon an early, incomplete definition of the design. This is highly recommended since most designs today must meet the specified trials speed under the force of a contractual penalty clause. It is also necessary to include a *power service margin* Ms to provide the added power needed in service to overcome the added resistance from hull fouling, waves, wind, shallow water effects, etc. When these two margins are incorporated, equation 67 for the trials design point (=) becomes:

$$P_B(1 - M_S) = P_E\,(1 + M_D)/(\eta_h\eta_o\eta_r\eta_s\eta_b\eta_t) \qquad [68]$$

The propeller is designed to achieve this equilibrium point on the initial sea trials, as shown in Figure 11.20. The design match point provides equilibrium between the engine curve: the prime mover at (1 - Ms) throttle and full rpm (the left side of the equality in equation 68), and the propeller load with (1 + Mo) included in the prediction (the right side of the equality).

The brake power P_B in equation 68 now represents the minimum brake power required from the prime mover. The engine(s) can, thus, be selected by choosing an engine(s) with a total Maximum Continuous Rating (or selected reduced engine rating for the application) which exceeds this required value:

$$MCR \geq P_B = P_E(1 + M_D)/(\eta_h\eta_o\eta_r\eta_s\eta_b\eta_t(1 - M_S)) \qquad [69]$$

Commercial ship designs have power design margin of 3 to 5% depending upon the risk involved in not achieving the specified trials speed. With explicit estimation of the air drag of the vessel, a power design margin of 3% might be justified for a fairly conventional hull form using the best parametric resistance prediction methods available today. The power design margin for Navy vessels usually needs to be larger due to the relatively larger (up to 25% compared with 3-8%) and harder to estimate appendage drag on these vessels. The U.S. Navy power design margin policy (42) includes a series of categories through which the margin decreases as the design becomes better defined and better methods are used to estimate the required power as shown in Table ll.IX.

Commercial designs typically have a power service margin of 15 to 25%, with the margin increasing from relatively low speed tankers to high-speed container ships. In principle, this should depend upon the dry docking interval; the trade route, with its expected sea and wind conditions, water temperatures, and hull fouling; and other factors.

The power output of a diesel prime mover varies as N' = NINo at constant throttle as shown in Figure 11.20, where N is the propeller rpm and No is the rated propeller rpm. Thus, diesel plants need a relatively larger power service margin to ensure that adequate power is available in the worst service conditions. The service margin might be somewhat smaller with steam or gas turbine prime movers since their power essentially varies as (2 - N')N' and is, thus, much less sensitive to propeller rpm. The power service margin might also be somewhat lower with a controllable pitch propeller since the pitch can be adjusted to enable to prime mover to develop maximum power under any service conditions. Conventionally powered naval vessels typically have power service margins of about 15% since the maximum power is being pushed hard to achieve the maximum speed and it is used only a relatively small amount of the ship's life. Nuclear powered naval vessels typically have higher power service margins since they lack the typical fuel capacity constraint and are, thus, operated more of their life at high powers.

It is important to note that in the margin approach outline above, the power design margin Mo is defined as a fraction of the resistance or effective power estimate, which is increased to provide the needed margin. The power service margin Ms, however, is defined as a fraction of the MCR that is reduced for the design match point on trials. This difference in the definition of the basis for the percentage of Mo and Ms is important. Note that if Ms were 20% this would increase P_B in equation 68 by 1/(1 - Ms) or 1.25, but if Ms were defined in the same manner as Mo it would only be increased by (1 + Ms) = 1.20. This potential 5% difference in

TABLE 11.IX U.S. Navy Power Design Margins (42)

Category	*Description*	M_D
1a	Early parametric prediction before the plan and appendage configuration	10%
1b	Preliminary design prediction made from the model P_E test	8%
2	Preliminary/contract design after P_S test with stock propeller and corrections	6%
3	Contract design after P_S test with model of actual propeller	2%

the sizing the main machinery is significant. Practice has been observed in Japan and also occasionally in the UK where both the power design margin and the power service margin are defined as increases of the smaller estimates, so precision in contractual definition of the power service margin is particularly needed when purchasing vessels abroad.

11.4.1.3 Effective power estimation

The choice of vessel dimensions and form parameters will influence and depend upon the resistance of the hull and the resulting choice of propulsor(s) and prime mover(s). The choice of machinery will influence the engine room size, the machinery weight, and the machinery center of gravity. Early estimates of the resistance of the hull can be obtained from SNAME Design Data Sheets, scaling model tests from a basis ship or geosim, standard series resistance data, or one of the resistance estimation software tools available today.

The most widely used parametric stage resistance model for displacement hulls (F_V ::;= 2) was developed by Holtrop and Mennen at MARIN (43, 44). This model has been implemented in the Power Prediction Program (PPP), which is available for teaching and design (40). This resistance model is used as the principal example here. Hollenbach presents a parametric resistance model intended to improve upon the Holtrop and Mennen method, particularly for modern, shallow draft, twin screw vessels (45).

The Holtrop and Mennen model is a complex, physics-based model for which the final coefficients were obtained by regression analysis of 334 model tests conducted at MARIN. (This particular model applies to displacement monohulls with characteristics in the ranges: 0.55 ::; C_P ::; 0.85; 3.90::; LIB ::; 14.9; 2.10::; *BIT::;* 4.00; 0.05::; Fn::; 1.00.) The model as implemented in PPP estimates resistance components using a modified Hughes method as follows:

$$R_T = (R_F + K_1R_F + R_W + R_B + R_{TR} + R_{APP} + R_A + R_{AIR})(1 + M_D) \quad [70]$$

where R_T is the total resistance, R_F is the frictional resistance, KJRF is the majority of the form drag, Rw is the wave making and wave breaking resistance, R_B is the added form drag due to the mounding of water above a bulbous bow that is too close to the free surface for its size, R_{TR} is the added form drag due to the failure of the flow to separate from the bottom of a hydrodynamic transom stern, R_{APP} is the appendage resistance, R_A is the correlation allowance resistance, R_{AJR} is the air resistance, and Mo is the power design margin. Holtrop and Mennen added the two special form drag components R_B and R_{TR} to achieve effective modeling of their model tests. The R_{AJR} and the power design margin were incorporated into the PPP program implementation to facilitate design work.

The Holtrop and Mennen model also include three separate models for the hull propeller interaction: \

1. wake fraction w,
2. thrust deduction t, and
3. relative rotative efficiency 11r'

The user needs to make a qualitative selection between a traditional closed stern or more modern open flow stern for a single screw vessel or select a twin screw model. The method also includes a rational estimation of the drag of each appendage based upon a first-principles drag estimate based upon its wetted surface Sj and a factor $(1 + K_2)$ that reflects an estimate of the local velocity at the appendage and its drag coefficient. The PPP program implements both a simple percentage of bare hull resistance appendage drag model and the more rational Holtrop and Mennen appendage drag model.

The input verification and output report from the PPP program are shown in Figure 11.21 for illustration.

The output includes all components of the resistance at a series of eight user-specified speeds and the resulting total resistance R_T; effective power PE; hull propeller interaction w, t, 11h' and 11r; and the thrust required of the propulsor(s) T_{reqd} = RJ(l - t). The design power margin as (1 + Mo) is incorporated within the reported total resistance, effective power, and required thrust for design convenience.

The model includes a regression model for the model-ship correlation allowance. If the user does not yet know the wetted surface of the hull or the half angle of entrance of the design waterplane, the model includes regression models that can estimate these hull characteristics from the other input dimensions and parameters. This resistance estimation model supports design estimates for most displacement monohulls and allows a wide range of tradeoff studies relative to resistance performance. In the example run shown in Figure 11.21, it can be seen that the bulbous bow sizing and location do not produce added form drag (RB = 0) and the flow clears off the transom stern (R_{TR}~ 0) above about 23 knots. The air drag is about 2% of the bare hull resistance in this case.

11.4.1.4 Propulsion efficiency estimation

Use of equation 69 to size the prime mover(s) requires the estimation of the six efficiencies in the denominator. Resistance and hull-propeller interaction estimation methods, such as the Holtrop and Mennen model as implemented in the PPP program, can provide estimates of the hull efficiency 11h and the relative rotative efficiency 11r' Estimation of the open water propeller efficiency 110 in early design will be discussed in the next subsection. Guidance for the sterntube and line bearing efficiencies are as follows (41):

$$\eta_s\eta_b = 0.98, \text{ for machinery aft}$$
$$= 0.97, \text{ for machinery amidship} \qquad [71]$$

The SNAME Technical and Research bulletins can provide guidance for the transmission efficiency with mechanical reduction gears (35):

$$\eta_t = \eta_g = \prod_i (1 - \ell_i) \qquad [72]$$

where $\ell_i = 0.010$ for each gear reduction, $\ell_i = 0.005$ for the thrust bearing, and $\ell_i = 0.010$ for a reversing gear path. Thus, a single reduction, reversing reduction gear with an internal thrust bearing used in a medium speed diesel plant would have a gearing efficiency of about $\eta_t = 0.975$. Note that since test bed data for low speed diesels usually does not include a thrust load, $\eta_t = 0.005$ should be included in direct connected low speed diesel plants to account for the thrust bearing losses in service.

With electric drive, the transmission efficiency must include the efficiency of the electrical generation, transmission, power conversion, electric motor, and gearing (if installed):

$$\eta_t = \eta_{gen}\eta_c\eta_m\eta_g \qquad [73]$$

where η_{gen} = electric generator efficiency, η_c = transmission and power conversion efficiency, η_m = electric motor efficiency, and η_g = reduction gear efficiency (equation 72)

The SNAME bulletin (35) includes data for this total transmission efficiency η_t depending upon the type of electrical plant utilized. In general, in AC generation/AC motor electrical systems η_t varies from about 88 to 95%, in AC/DC systems η_t varies from about 85 to 90%, and in DC/DC systems η_t varies from about 80 to 86% each increasing with the rated power level of the installation. Further, all the bearing and transmission losses increase as a fraction of the transmitted power as the power drops below the rated condition.

11.4.1.5 Propeller design optimization

The open water propeller efficiency η_o is the most significant efficiency in equation 69. The resistance and hull-propeller interaction estimation yields the wake fraction w and the required total thrust from the propeller or propellers,

$$T_{reqd} = R_T/(1 - t) \qquad [74]$$

assuming a conventional propeller is used. Alexander (46) provides a discussion of the comparable issues when using

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Department of Naval Architecture and Marine Engineering

Power Prediction Program (PPP-1.8) by M. G. Parsons

Source: 1. Holtrop, J., & Mennen, G.G.J., "An Approximate Power Prediction Method," International Shipbuilding Progress, Vol.29, No.335, July, 1982.
2. Holtrop, J., "A Statistical Reanalysis of Resistance and Propulsion Data," International Shipbuilding Progress, Vol.31, No.363, Nov., 1984.

Run Identification: SDC Test Powering

Input Verification:

Length of Waterline LWL (m)	=	205.00
Maximum Beam on LWL (m)	=	32.00
Depth at the Bow (m)	=	20.00
Mean Draft (m)	=	10.00
Draft Forward (m)	=	10.00
Draft Aft (m)	=	10.00
Block Coefficient on LWL CB	=	0.5716
Prismatic Coefficient on LWL CP	=	0.5833
Midship Coefficient to LWL CM=CX	=	0.9800
Waterplane Coefficient on LWL CWP	=	0.7500
Center of Buoyancy LCB (% LWL; + Fwd)	=	-0.7500
Center of Buoyancy LCB (m from FP)	=	104.04
Molded Volume (m^3)	=	37497.0
Deck House/Cargo Frontal Area (m^2)	=	300.00
Water Type	=	Salt@15C
Water Density (kg/m^3)	=	1025.87
Kinematic Viscosity (m^2/s)	=	0.118831E-05
Appen. Drag (% Bare Hull Resistance)	=	5.00
Bulb Section Area at Station 0 (m^2)	=	20.00
Vertical Center of Bulb Area (m)	=	4.00
Transom Immersed Area (m^2)	=	16.00
Stern Type	=	Normally Shaped
Design Margin on RT,PE,REQ.THR (%)	=	5.00
Propulsion Type	=	SS, Conv.
Propeller Diameter (m)	=	8.00
Propeller Expanded Area Ratio Ae/Ao	=	0.7393
Wetted Surface (m^2)	=	7381.24
Half Angle of Entrance (deg)	=	12.11

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Power Prediction Program (PPP-1.8) by M. G. Parsons

Source: 1. Holtrop, J., & Mennen, G.G.J., "An Approximate Power Prediction Method," International Shipbuilding Progress, Vol.29, No.335, July, 1982.
2. Holtrop, J., "A Statistical Reanalysis of Resistance and Propulsion Data," International Shipbuilding Progress, Vol.31, No.363, Nov., 1984.

Run Identification: SDC Test Powering

Speed, Resistance Coefficients and Frictional Resistance RF(N):

V(kts)	V(m/s)	FN	SLRATIO	CF	CR	CA	RF
15.00	7.72	0.1721	0.5784	0.001478	0.000441	0.000352	333139.8
17.00	8.75	0.1951	0.6555	0.001455	0.000472	0.000352	421443.8
19.00	9.77	0.2180	0.7326	0.001436	0.000549	0.000352	519426.3
21.00	10.80	0.2409	0.8097	0.001419	0.000674	0.000352	626970.3
23.00	11.83	0.2639	0.8869	0.001404	0.000878	0.000352	743972.3
25.00	12.86	0.2868	0.9640	0.001390	0.001108	0.000352	870339.8
27.00	13.89	0.3098	1.0411	0.001377	0.001260	0.000352	1005989.3
29.00	14.92	0.3327	1.1182	0.001366	0.001465	0.000352	1150844.6

Remaining Resistance Components (N):

V(kts)	Form RF*K1	Appendage RAPP	Wave RW	Bulb RB	Transom RTR	Correlation RA	Air Drag RAIR
15.00	53277.7	21627.6	12091.4	24.6	34017.7	79469.8	13476.4
17.00	67399.9	27907.1	36487.5	30.0	32781.2	102074.5	17309.7
19.00	83069.8	35893.0	88011.8	35.3	27316.6	127504.8	21622.2
21.00	100268.9	46238.6	180775.2	40.2	16717.9	155760.8	26413.8
23.00	118980.5	60471.7	346357.5	44.9	78.7	186842.3	31684.6
25.00	139190.0	78214.1	554702.9	49.2	0.0	220749.4	37434.5
27.00	160883.9	96303.5	759144.4	53.2	0.0	257482.1	43663.6
29.00	184050.0	119248.5	1050018.4	57.0	0.0	297040.4	50371.9

Resistance, Effective Power, Propulsion Factors and Required Thrust

V(kts)	RT(N)	PE(kW)	w	t	REQ.THR(N)	etaH	etaRR
15.00	574481.3	4433.04	0.2402	0.1834	703483.2	1.0748	0.9931
17.00	740705.4	6477.82	0.2397	0.1834	907033.5	1.0741	0.9931
19.00	948023.8	9266.33	0.2393	0.1834	1160906.0	1.0736	0.9931
21.00	1210844.9	13081.05	0.2390	0.1834	1482744.5	1.0731	0.9931
23.00	1562854.0	18491.88	0.2387	0.1834	1913798.5	1.0726	0.9931
25.00	1995714.0	25666.88	0.2384	0.1834	2443858.8	1.0722	0.9931
27.00	2439696.3	33887.09	0.2381	0.1834	2987538.8	1.0718	0.9931
29.00	2994212.3	44669.94	0.2379	0.1834	3666573.5	1.0715	0.9931

Design Margin Has Been Included in RT, PE, and REQ.THR = RT/(1-t).

Figure 11.21 Sample Power Prediction Program (PPP) Output (40) waterjet propulsion. For large moderately cavitating propellers, the Wageningen B-Screw Series is the commonly used preliminary design model (47). An optimization program which selects the maximum open water efficiency Wageningen B-Screw Series propeller subject to a 5% or 10% Burrill back cavitation constraint (41) and diameter constraints is implemented as the Propeller Optimization Program (POP), which is available for teaching and design (40). This program utilizes the NeIder and Mead Simplex Search with an External Penalty Function (48) to obtain the optimum design. A sample design run with the Propeller Optimization Program (POP) is shown in Figure 11.22.

The program can establish the operating conditions for a specified propeller or optimize a propeller design for given operating conditions and constraints. A sample optimization problem is shown. This provides an estimate of the open water efficiency Tlo needed to complete the sizing of the propulsion machinery using equation 69.

Useful design charts for the maximum open water efficiency Wageningen B-Screw Series propellers are also available for two special cases. Bernitsas and Ray present results for the optimum rpm propeller when the diameter is set by the hull and clearances (49) and for the optimum diameter propeller when a directly connected low speed diesel ~ngine sets the propeller rpm (50). In using these design charts, the cavitation constraint has to be imposed externally using Keller's cavitation criterion or Burrill's cavitation constraints (41, 51) or a similar result.

Initial propeller design should also consider the tradeoff among blade number Z, propeller rpm N_p, open water efficiency Tlo' and potential resonances between the blade rate propeller excitation at ZNp (cpm) and predicted hull natural frequencies. Hull natural frequencies can be estimated in the early parametric design using methods presented by Todd (52).

11.4.2 Maneuvering Performance Estimation

The maneuvering characteristics of a hull are directly affected by its fundamental form and LCG as well as its rudder(s) size and location. Recent IMO requirements recommend performance in turns, zigzag maneuvers, and stop-

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Propeller Optimization Program (POP-1.5) by M.G. Parsons

  Source:1. Oosterveld, M. W. C., and Van Oossanen, P.,
            "Further Computer-Analyzed Data of the Wageningen
            B-Screw Series", International Shipbuilding
            Progress, Vol. 22, No. 251, July, 1975.
         2. Parsons, M. G., "Optimiztion Methods for Use in
            Computer-Aided Ship Design", Proceedings of the
            First SNAME STAR Symposium, 1975

Wageningen B-Screw Series Propeller Preliminary Design

 *** Eta 0 Reduced by 2% When Controllable Pitch ***

Run Identification:  SDC Test Optimization
 Input Data:
     Optimization Run

     Fixed-Pitch Propeller
     Number of Propeller Blades             =        4
     Required Propeller Thrust (kN)         =      444.8
     Ship Speed Vk (knots)                  =      15.00
     Wake Fraction w                        =      0.115
     Depth of Shaft below Waterline (m)     =       4.40
     Water Type                             =    salt@15C
     Water Density Rho (kg/m^3)             =    1025.87
     Kinematic Viscosity Nu (m^2/sec)       =   0.118831E-05
     Burrill Back Cavitation Constraint     =         5%

     Initial Expanded Area Ratio Ae/Ao      =      0.750
     Initial Pitch Diameter Ratio P/Dp      =      0.900
     Initial Propeller Diameter Dp (m)      =       4.00
     Minimum Diameter Constraint Dpmin (m)  =       1.15
     Maximum Diameter Constraint Dpmax (m)  =       4.60

 Optimal Design Results:
     Propeller Diameter Dp (m)                =      4.60
     Propeller Pitch P (m)                    =      3.95
     Pitch Diameter Ratio P/Dp                =    0.8589
     Expanded Area Ratio Ae/Ao                =    0.6792
     Propeller Revolutions per Minute (rpm)   =    149.46
     Advance Coefficient J                    =    0.5966
     Thrust Coefficient KT                    =    0.1564
     Torque Coefficient KQ                    =   0.02251
     Propeller Open Water Efficiency Eta 0    =     0.660
     Propeller Thrust (kN)                    =     444.8
     Reynolds Number RN                       = 0.406E+08
     Cavitation Number Sigma                  =    0.4152
     Optimization Search Evaluation Count     =        64
```

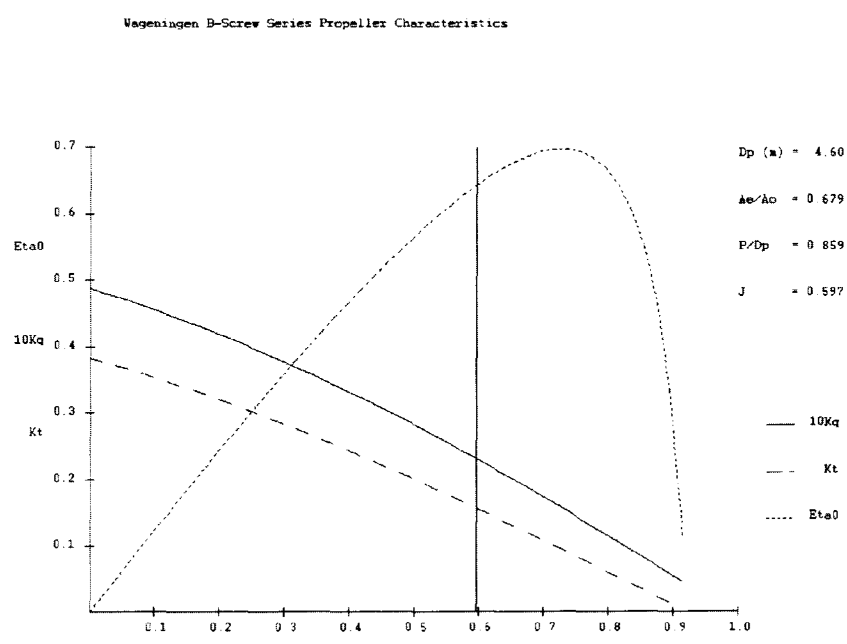

Figure 11.22 Sample Propeller Optimization Program (POP) Output (40)

ping. Thus, it is incumbent upon the designer to check basic maneuvering characteristics of a hull during the parametric stage when the overall dimensions and form coefficients are being selected. This subsection will illustrate a parametric design capability to assess course stability and turnability. This performance presents the designer with a basic tradeoff since a highly course stable vessel is hard to turn and vice versa.

Clarke et al (53) and Lyster and Knights (54) developed useful parametric stage maneuvering models for displacement hulls. Clarke et al used the linearized equations of motion in sway and yaw to develop a number of useful measures of maneuverability. They estimated the hydrodynamics stability derivatives in terms of the fundamental parameters of the hull form using regression equations of data from 72 sets of planar motion mechanism and rotating arm experiments and theoretically derived independent variables. Lyster and Knights obtained regression equations of turning circle parameters from full-scale maneuvering trials. These models have been implemented in the Maneuvering Prediction Program (MPP), which is also available for teaching and design (40). In MPP, the Clarke hydrodynamic stability derivative equations have been extended by using corrections for trim from Inoue et al (55) and corrections for finite water depth derived from the experimental results obtained by Fugino (56).

Controls-fixed straight-line stability is typically assessed using the linearized equations of motion for sway and yaw (57). The sign ofthe Stability Criterion C, which involves the stability derivatives and the vessel LCG position, can determine stability. A vessel is straight-line course stable if:

$$C = Y_v'(N_r' - m'x_g') - (Y_r' - m')N_v' > 0 \qquad [75]$$

where m' is the non-dimensional mass, $x_{g'}$ is the longitudinal center of gravity as a decimal fraction of ship length plus forward of amidships, and the remaining terms are the normal sway force and yaw moment stability derivatives with respect to sway velocity v and yaw rate r.

Clarke (53) proposed a useful turnability index obtained by solving Nomoto's second-order in r lateral plane equation of motion for the change in heading angle resulting from a step rudder change after vessel has traveled one ship length:

$$P_c = | \psi/\delta |_{t'=1} \qquad [76]$$

This derivation follows earlier work by Norrbin that defined a similar PI parameter. Clarke recommended a design value of at least 0.3 for the Pc index. This suggests the ability to turn about 10 degrees in the first ship length after the initiation of a full 35 degree rudder command.

Norrbin's index is obtained by solving the simpler first-order Nomoto's equation of motion for the same result. It can be calculated as follows:

$$P_1 = | \psi/\delta |_{t'=1} = |K'|(1 - |T'| (1 - e^{-t/|T'|})) \qquad [77]$$

where K' and T' are the rudder gain and time constant, respectively, in the first-order Nomoto's equation:

$$T'dr'/dt' + r' = K'\delta \qquad [78]$$

where r' is the nondimensional yaw rate and () is the rudder angle in radians. Values for a design can be compared with the recommended minimum of 0.3 (0.2 for large tankers) and the results of a MarAd study by Barr and the European COST study that established mean lines for a large number of acceptable designs. This chart is presented in Figure 11.23.

Clarke also noted that many ships today, particularly those with full hulls and open flow to the propeller, are course unstable. However, these can still be maneuvered successfully by a helmsman if the phase lag of the hull and the steering gear is not so large that it cannot be overcome by the anticipatory abilities of a trained and alert helmsman. This can be assessed early in the parametric stage of design by estimating the phase margin for the hull and steering gear and comparing this to capabilities found for typical helmsmen in maneuvering simulators. Clarke derived this phase margin from the linearized equations of motion and concluded that a helmsman can safely maneuver a course unstable ship if this phase margin is above about -20 degrees. This provides a valuable early design check for vessels that need to be course unstable.

Lyster and Knights (53) obtained regression equations for standard turning circle parameters from maneuvering trials of a large number of both single- and twin-screw vessels. Being based upon full-scale trials, these results represent the fully nonlinear maneuvering performance of these vessels. These equations predict the advance, transfer, tactical diameter, steady turning diameter, and steady speed in a turn from hull parameters.

The input and output report from a typical run of the Maneuvering Prediction Program (MPP) is shown in Figure 11.24. More details ofthis program are available in the manual (40). The program estimates the linear stability derivatives, transforms these into the time constants and gains for Nomoto's first- and second-order maneuvering equations, and then estimates the characteristics described above. These results can be compared to generalized data from similar ships (57) and Figure 11.23. The example ship analyzed is course unstable since $C < 0$, with good turnability as indicated by $Pc = 0.46$, but should be easily controlled by a helmsman since the phase margin is $2.4^o > -20^o$. Norrbin's

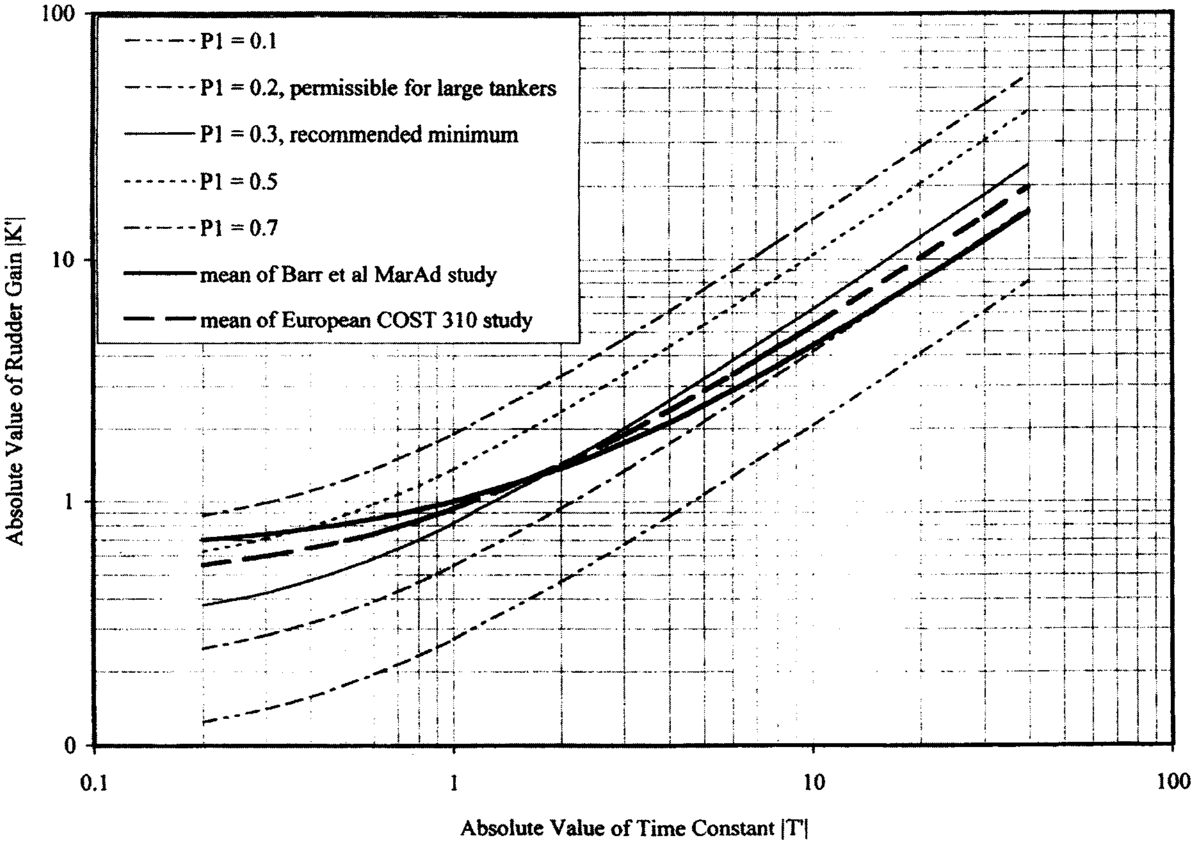

Figure 11.23 Norrbin's Turning Index versus |K′| and |T′|

turning index can be seen to be favorable in Figure 11.23. The advance of 2.9 L and tactical diameter of 3.5 L are well below the IMO recommended 4.5 L and 5.0 L, respectively. If these results were not acceptable, the design could be improved by changing rudder area and/or modifying the basic proportions of the hull.

11.4.3 Seakeeping Performance Estimation

The seakeeping performance (58) can be a critical factor in the conceptual design of many vessels such as offshore support vessels, oceanographic research vessels, and warships. It is only secondary in the parametric design of many conventional commercial vessels. The basic hull sizing and shape will affect the seakeeping capabilities of a vessel as noted in the discussion associated with equation 21.

Thus, it may be incumbent upon the designer to check the basic seakeeping characteristics of a hull during the parametric stage when the overall dimensions and form coefficients are being selected. This subsection will illustrate a parametric design capability to assess seakeeping performance in a random seaway. Coupled five (no surge) and six degree-of-freedom solutions in a random seaway are desired. From this, typically only the three restored motions of heave, pitch, and roll and the vertical wave bending moment are of interest in the parametric stage of conceptual design.

11.4.3.1 Early estimates of motions natural frequencies

Effective estimates can often be made for the three natural frequencies in roll, heave, and pitch based only upon the characteristics and parameters of the vessel. Their effectiveness usually depends upon the hull form being close to the norm.

An approximate roll natural period can be derived using a simple one degree-of-freedom model yielding:

$$T_\phi = 2.007\ k_{11}/\sqrt{GM_T} \qquad [77]$$

where k_{11} is the roll radius of gyration, which can be related to the ship beam using:

$$k_{11} = 0.50\ \kappa\ B \qquad [78]$$

with $0.76 \le \kappa \le 0.82$ for merchant hulls and $0.69 \le \kappa \le 1.00$ generally.

Using $\kappa = 0.80$, we obtain the easy to remember result $k_{11} \approx 0.40B$. Katu (59) developed a more complex parametric

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Maneuvering Prediction Program (MPP-1.3) by M.G. Parsons

  References:  Clarke,D., Gedling,P., and Hine,G.,
               "The Application of Manoeuvring Criteria in Hull
                Design using Linear Theory," Trans. RINA, 1983
               Lyster, C., and Knights, H. L.,
               "Prediction Equations for Ships' Turning Circles,"
                Trans. NECIES, 1978-1979

 Run Identification: SDC Test Maneuvering

 Input Verification:

      Length of Waterline LWL (m)                  =    148.00
      Maximum Beam on LWL (m)                      =     32.28
      Mean Draft (m)                               =      9.00
      Draft Forward (m)                            =      9.00
      Draft Aft (m)                                =      9.00
      Block Coefficient on LWL CB                  =    0.7000
      Molded Volume (m^3)                          =  30097.87
      Center of Gravity LCG (%LWL; + Fwd)          =   -0.5000
      Center of Gravity LCG (m from FP)            =     74.74
      Midships to Rudder CE XR (%LWL; + Aft)       =   49.0000
      Rudder Center of Effort XR (m from FP)       =    146.52
      Initial Ship Speed (knots)                   =     16.00
      Initial Ship Speed (m/s)                     =    8.2310
      Water Type                                   = Salt@15C
      Water Density (kg/m^3)                       =   1025.87
      Kinematic Viscosity (m^2/s)                  =  0.118831E-05
      Yaw Radius of Gyration K33/LWL               =    0.2500
      Water Depth to Ship Draft Ratio H/T          =   1000.00
      Steering Gear Time Constant (s)              =      2.50
      Total Rudder Area - Fraction of LWL*T        =    0.0219
      Number of Propellers                         =         2
      Number of Rudders                            =         2
      Submerged Bow Area - Fraction of LWL*T       =    0.0160
```

```
Run Identification: SDC Test Maneuvering

   Linear Maneuvering Derivatives

Nondimensional Mass                 M prime     =  0.018569
Nondimensional Mass Moment          I sub zz    =  0.001161

Sway Velocity Derivative            Y sub v     = -0.024483
Sway Acceleration Derivative        Y sub v dot = -0.013466

Yaw Velocity Derivative             N sub v     = -0.006917
Yaw Acceleration Derivative         N sub v dot = -0.001079

Sway Velocity Derivative            Y sub r     =  0.004155
Sway Acceleration Derivative        Y sub r dot = -0.001205

Yaw Velocity Derivative             N sub r     = -0.003398
Yaw Acceleration Derivative         N sub r dot = -0.000628

Sway Rudder Derivative              Y sub delta =  0.003995
Yaw Rudder Derivative               N sub delta = -0.001958

   Time Constants and Gains for Nomoto's Equation

Dominant Ship Time Constant    T1 prime       =   -7.2207
Ship Time Constant             T2 prime       =    0.4145
Numerator Time Constant        T3 prime       =    0.8821
Numerator Time Constant        T4 prime       =    0.2250

1st Order Eqn. Time Constant   T prime        =   -7.6882
Rudder Gain Factor             K prime        =    4.0253
Rudder Gain Factor             K sub v prime  =   -2.2066

Steering Gear Time Constant    TE prime       =    0.1390

   Evaluation of Turning Ability and Stability

Inverse Time Constant          1/|T prime|    =    0.1301
Inverse Gain Factor            1/|K prime|    =    0.2484

Clarke's Turning Index                        P =    0.4634
Linear Dynamic Stability Criterion            C =-0.0000188

Vessel is hydrodynamically open loop course unstable

Closed Loop Phase Margin with Steering Engine  =    0.6187 degrees


 Approach Speed                          =     16.00 knots

 Rudder Angle                            =     35.00 degrees

 Steady Turning Diameter                 =    511.02 meters
 Tactical Diameter                       =    531.33 meters
 Advance                                 =    432.71 meters
 Transfer                                =    230.34 meters
 Steady Speed in Turn                    =     10.33 knots
```

Figure 11.24 Sample Maneuvering Prediction Program (MPP) Output (40)

model for estimating the roll natural period that yields the alternative result for the parameter κ,

$$\kappa = 0.724\sqrt{(C_B(C_B + 0.2) - 1.1(C_B + 0.2) \times (1.0 - C_B)(2.2 - D/T) + (D/B)^2)} \qquad [79]$$

Roll is a lightly damped process so the natural period can be compared directly with the dominant encounter period of the seaway to establish the risk of resonant motions. The encounter period in long-crested oblique seas is given by:

$$T_e = 2\pi / (\omega - (V\omega^2 / g)\cos\theta_w) \qquad [80]$$

where ω is the wave frequency, V is ship speed, and θ_w is the wave angle relative to the ship heading with $\theta_w = 0°$ following seas, $\theta_w = 90°$ beam seas, and $\theta_w = 180°$ head seas. For reference, the peak frequency of an ISSC spectrum is located at $4.85T_1^{-1}$ with T_1 the characteristic period of the seaway. An approximate pitch natural period can also be derived using a simple one degree-of-freedom model yielding:

$$T_\theta = 2.007\ k_{22}/\sqrt{GM_L} \qquad [81]$$

where now k_{22} is the pitch radius of gyration, which can be related to the ship length by noting that $0.24L \le k_{22} \le 0.26L$. An alternative parametric model reported by Lamb (14) can be used for comparison:

$$T_\theta = 1.776\ C_{WP}^{-1}\sqrt{(TC_B(0.6 + 0.36B/T))} \qquad [82]$$

Pitch is a heavily-damped (non resonant) mode, but early design checks typically try to avoid critical excitation by at least 10%.

An approximate heave natural period can also be derived using a simple one degree-of-freedom model. A resulting parametric model has been reported by Lamb (14):

$$T_h = 2.007 \sqrt{T C_B (B/3T + 1.2)/C_{WP}} \qquad [83]$$

Like pitch, heave is a heavily damped (non resonant) mode. Early design checks typically try to avoid having $T_h = T_\phi$, $T_h = T_e$, $2T_h = T_e$, $T_\phi = T_e$ or $T_\phi = 2T_e$ which could lead to significant mode coupling. For many large ships, however, these conditions often cannot be avoided.

11.4.3.2 Vertical plane estimates for cruiser stern vessels

Loukakis and Chryssostomidis (60) used repeated seakeeping analyses to provide information for parameter stage estimation of the vertical plane motions of cruiser stem vessels based on the Series 60 family of vessels.

11.4.3.3 Estimates by linear seakeeping analysis

While most seakeeping analysis codes require a hull design and a set of hull offsets, useful linear seakeeping analysis is still feasible at the parameter stage of early design. The SCORES five degree-of-freedom (no surge) linear seakeeping program (61) has been adapted to personal computers for use in parametric design. This program was specifically selected because of its long period of acceptance within the industry and its use of the Lewis form transformations to describe the hull. The Lewis Forms require the definition of only the Section Area Curve, the Design Waterline Curve, and the keel profile for the vessel. Hull offsets are not needed.

The SCORES program was adapted to produce the Seakeeping Prediction Program (SPP), which has been developed for teaching and design (40). This program supports the description of the seaway by a Pierson-Moskowitz, ISSC, or JONSWAP spectrum. It produces more accurate estimates of the roll, pitch, and heave natural periods. It also performs a spectral analysis of the coupled five degree-of-freedom motions and the vertical wave bending moment, the horizontal wave bending moment, and the torsional wave bending moment. Since SPP is intended for use in the earliest stages of parametric design, only the results for roll, pitch, heave, and the three moments are output (sway and yaw while in the solution are suppressed). The statistical measures of RMS, average, significant (average of the 1/3 highest), and the average of the 1/10 highest values are produced for all six of these responses. An estimated extreme design value is also produced for the three bending moments using:

$$\text{design extreme value} = \text{RMS} \sqrt{2\ln(N/\alpha)} \qquad [84]$$

where the number of waves $N = 1000$ is used, typical of about a 3 1/2 hour peak storm, and $\alpha = 0.01$ is used to model a 1% probability of exceedance. These design moments can be used in the initial midship section design.

The Seakeeping Prediction Program (SPP) can be'used in two ways in early design. With only ship dimensions and hull form parameters available, the program will approximate the Section Area Curve and the Design Waterline Curve for the hull using 5th-order polynomial curves. In its current form, the model can include a transom stem, but does not model a bulbous bow, which will have a relatively secondary effect on the motions. This modeling is effective for hulls without significant parallel midbody. The program can also accept station data for the Section Area Curve and the Design Waterline Curve if these have been established by hydrostatic analysis in the early design process.

Because the linear seakeeping analysis uses an ideal fluid (inviscid flow) assumption, which will result in serious underprediction of roll damping, the user can include a realistic estimate of viscous roll damping by inputting a fraction of critical roll damping ζ estimate. This is necessary to produce roll estimates that are useful in design. A value of $\zeta = 0.10$ is typical of normal hulls without bilge keels, with bilge keels possibly doubling this value.

The input and selected portions of the output report from a typical run of the Seakeeping Prediction Program (SPP) are shown in Figure 11.25. More details of this program are available in the SCORES documentation (61) and the SPP User's Manual (40). In this particular example, the heave and pitch natural frequencies are almost identical indicating highly coupled vertical plane motions. The vessel experiences a 6° significant roll at a relative heading of $\theta_W = 60°$ in an ISSC spectrum sea with significant wave height $H_S = 2.25$ m and characteristic period $T_1 = 10$ s (Sea State 4). This ship will, therefore, occasionally experience roll as high as 12° in this seaway. If these predicted results were not acceptable, the design could be improved by adding bilge keels or roll fins or by modifying the basic proportions of the hull, particularly beam, C_{WP}, and C_{VP}.

11.5 PARAMETRIC MODEL DEVELOPMENT

The parametric study of ship designs requires models that relate form, characteristics, and performance to the fundamental dimensions, form coefficients, and parameters of the design. Various techniques can be used to develop these models. In pre-computer days, data was graphed on Cartesian, semi-log, or log-log coordinates and if the observed relationships could be represented as straight lines in these coordinates linear ($y = a_0 + a_1x$), exponential ($y = ab^x$), and geometric ($y = ax^b$) models, respectively, were developed. With the development of statistical computer software, mul-

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Seakeeping Prediction Program (SPP-1.5) by M.G. Parsons

Reference: Raff, A. I., "Program SCORES - Ship Structural Response in Waves", Ship Structures Committee Report SSC-230, 1972

Hull Data Identification:

Run Identification: SDC Test Seakeeping

Input Verification:

Length of Waterline LWL (m)	=	38.00
Vessel Displacement (tonnes)	=	499.9
Vertical Center of Gravity VCG (m)	=	3.50
Roll Radius of Gyration k11 (m)	=	3.80
Fraction of Critical Roll Damping	=	0.1300
Ship Speed (knots)	=	12.50
Ship Heading Relative to Waves (deg)	=	60.00
Water Type	=	Salt@15C
Water Density Rho (kg/m^3)	=	1025.87
ISSC Two Parameter Spectrum Excitation		
Significant Wave Height (m)	=	2.25
Characteristic Wave Period (s)	=	10.00
Lower Freq. Integration Limit (rad/s)	=	0.30
Upper Freq. Integration Limit (rad/s)	=	2.00

Sta.	Beam[m]	Area[m^2]	Draft[m]	Weight[t]
0	0.00	0.00	0.00	20.0
1	3.43	3.71	2.50	35.0
2	6.11	10.11	2.50	38.0
3	7.92	16.39	2.50	60.0
4	8.90	20.74	2.50	60.0
5	9.18	22.26	2.50	60.0
6	8.97	20.80	2.50	60.0
7	8.47	16.81	2.50	60.0
8	7.85	11.22	2.50	47.0
9	7.10	5.30	2.50	40.0
10	6.20	0.50	0.13	20.0

Motion Natural Frequencies and Periods:

Heave Natural Frequency = 1.555 rad/s   Heave Natural Period = 4.04 sec.

Pitch Natural Frequency = 1.574 rad/s   Pitch Natural Period = 3.99 sec.

Roll Natural Frequency = 0.697 rad/s   Roll Natural Period = 9.02 sec.

Roll Damping Results:

Roll Wave Damping = 0.844E+01

Added Viscous Roll Damping = 0.152E+03

Seakeeping Response Results:

Ship Speed = 12.5 knots = 6.43 m/s

Wave Angle [with Head Seas 180 deg.] = 60.0 deg.

ISSC Two Parameter Spectrum - Sign.Height = 2.25 m   Char. Period = 10.00 s

Wave Input and Response Amplitude Spectra:

Freq. r/s	Wave Amp. m^2s	Heave m^2s	Pitch deg.^2s	Roll deg.^2s	Vert. Mom. (t-m)^2s	Lat. Mom. (t-m)^2s	Tors. Mom. (t-m)^2s
0.300	0.007	0.007	0.001	0.002	0.121E+00	0.217E+00	0.448E-03
0.394	0.523	0.515	0.113	0.481	0.215E+02	0.492E+02	0.250E+00
0.489	0.933	0.904	0.470	2.455	0.672E+02	0.201E+03	0.228E+01
0.583	0.714	0.674	0.711	4.783	0.768E+02	0.299E+03	0.703E+01
0.678	0.442	0.401	0.771	7.044	0.719E+02	0.322E+03	0.151E+02
0.772	0.263	0.226	0.733	9.454	0.795E+02	0.309E+03	0.277E+02
0.867	0.159	0.126	0.652	12.087	0.109E+03	0.283E+03	0.460E+02
0.961	0.099	0.071	0.556	14.286	0.159E+03	0.253E+03	0.682E+02
1.056	0.063	0.040	0.457	14.422	0.225E+03	0.225E+03	0.842E+02
1.150	0.042	0.023	0.363	11.968	0.297E+03	0.205E+03	0.841E+02
1.244	0.029	0.013	0.275	8.581	0.367E+03	0.192E+03	0.722E+02
1.339	0.020	0.007	0.198	5.756	0.421E+03	0.183E+03	0.577E+02
1.433	0.014	0.004	0.133	3.767	0.450E+03	0.172E+03	0.450E+02
1.528	0.010	0.002	0.081	2.422	0.446E+03	0.159E+03	0.345E+02
1.622	0.008	0.001	0.043	1.501	0.407E+03	0.143E+03	0.253E+02
1.717	0.006	0.000	0.018	0.868	0.336E+03	0.122E+03	0.169E+02
1.811	0.004	0.000	0.005	0.449	0.246E+03	0.988E+02	0.944E+01
1.906	0.003	0.000	0.000	0.219	0.153E+03	0.734E+02	0.363E+01
2.000	0.003	0.000	0.001	0.143	0.748E+02	0.489E+02	0.669E+00

Wave Input and Response Amplitude Statistics:

	m	m	deg.	deg.	t-m	t-m	t-m
R.M.S.	0.562	0.533	0.726	3.083	0.194E+02	0.177E+02	0.753E+01
Ave.	0.702	0.666	0.907	3.853	0.242E+02	0.221E+02	0.941E+01
Signif.	1.123	1.066	1.452	6.165	0.387E+02	0.354E+02	0.151E+02
Ave 1/10	1.432	1.359	1.851	7.861	0.494E+02	0.451E+02	0.192E+02
Design Value with N=1000 and alpha=0.01					0.929E+02	0.849E+02	0.361E+02

Figure 11.25 Sample Seakeeping Prediction Program (SPP) Output (40)

tiple linear regression has become a standard tool for developing models from data for similar vessels. More recently, Artificial Neural Networks (ANN) have begun to be used to model nonlinear relationships among design data. This Section provides an introduction to the development of ship models from similar ship databases using multiple linear regression and neural networks.

11.5.1 Multiple Linear Regression Analysis

Regression analysis is a numerical method which can be used to develop equations or models from data when there is no or limited physical or theoretical basis for a specific model. It is very useful in developing parametric models for use in early ship design. Highly effective capabilities are now available in personal productivity software, such as Microsoft Excel.

In multiple linear regression, a minimum least squares error curve of a particular form is fit to the data points. The curve does not pass through the data, but generalizes the data to provide a model that reflects the overall relationship between the dependent variable and the independent variables. The effectiveness (goodness of fit) of the modeling can be assessed by looking at the following statistical measures:

1. R = Coefficient of Correlation which expresses how closely the data clusters around the regression curve (0 ~ R ~ 1, with 1 indicating that all the data is on the curve).
2. R^2 = Coefficient of Determination which expresses the fraction of the variation of the data about its mean that is captured by the regression curve (0 ~ R2 ~ 1, with 1 indicating that all the variation is reflected in the curve).
3. SE = Standard Error which has units of the dependent variable and is for large n the standard deviation of the error between the data and the value predicted by the regression curve.

The interpretation of the regression curve and Standard Error is illustrated in Figure 11.26 where for an example TED capacity is expressed as a function of Cubic Number CN. The regression curve will provide the mean value for the population that is consistent with the data. The Standard Error yields the standard deviation σ for the normal distribution (in the limit of large n) of the population that is consistent with the data.

The modeling process involves the following steps using Excel or a similar program:

1. select independent variables from first principles or past successful modeling,
2. observe the general form of the data on a scatter plot,
3. select a candidate equation form that will model the data most commonly using a linear, multiple linear, polynomial, exponential, or geometric equation,
4. transform the data as needed to achieve a linear multiple regression problem (for example, the exponential and geometric forms require log transformations),
5. regress the data using multiple linear regression,
6. observe the statistical characteristics R, R^2, and SE, and
7. iterate on the independent variables, model form, etc. to provide an acceptable fit relative to the data quality.

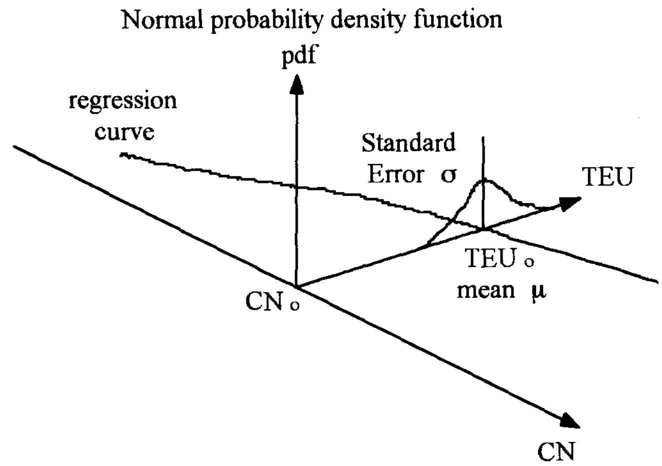

Figure 11.26 Probabilistic Interpretation of Regression Modeling

11.5.2 Neural Networks

An Artificial Neural Network (ANN) is a numerical mapping between inputs and output that is modeled on the networks of neurons in biological systems (62, 63). An ANN is a layered, hierarchical structure consisting of one input layer, one output layer and one or more hidden layers located between the input and output layers. Each layer has a number of simple processing elements called neurons (or nodes or units). Signal paths with multiplicative weights w interconnect the neurons. A neuron receives its input(s) either from the outside of the network (that is, neurons in the input layer) or from the other neurons (those in the input and hidden layers). Each neuron computes its output by its transfer (or activation) function and sends this as input to other neurons or as the final output from the system. Each neuron can also have a bias constant b included as part of its transfer function. Neural networks are effective at extracting nonlinear relationships and models from data. They have been used to model ship parametric data (64, 65) and shipbuilding and shipping markets (66).

A typical feedforward neural network, the most commonly used, is shown schematically in Figure 11.27. In a feedforward network the signal flow is only in the forward direction from one layer to the next from the input to the output. Feedforward neural networks are commonly trained by the supervised learning algorithm called backpropagation. Backpropagation uses a gradient decent technique to adjust the weights and biases of the neural network in a backwards, layer-by-layer manner. It adjusts the weights and biases until the vector of the neural network outputs for the corresponding vectors of training inputs approaches the required vector of training outputs in a minimum root mean square (RMS) error sense. The neural network design task involves selection of the training input and output vectors, data preprocessing to improve training time, identification of an effective network structure, and proper training of the network. The last issue involves a tradeoff between overtraining and under training. Optimum training will capture the essential information in the training data without being overly sensitive to noise. Li and Parsons (67) present heuristic procedures to address these issues.

The neurons in the input and output layers usually have simple linear transfer functions that sum all weighted inputs and add the associated biases to produce their output signals. The inputs to the input layer have no weights.

The neurons in the hidden layer usually have nonlinear transfer functions with sigmoidal (or S) forms the most common. Neuron j with bias b_j and n inputs each with signal x_i and weight w_{ij} will have a linearly combined activation signal Z_j as follows:

$$z_j = \sum_{i=1}^{n} w_{ij}\, x_i + b_j \qquad [85]$$

A linear input or output neuron would just have this Z_j as its output. The most common nonlinear hidden layer transfer functions use the exponential logistic function or the hyperbolic tangent function, respectively, as follows:

$$y_j = (1 + e^{-z_j})^{-1} \qquad [86]$$

$$y_j = \tanh(z_j) = (e^{z_j} - e^{-z_j})/(e^{z_j} + e^{-z_j}) \qquad [87]$$

These forms provide continuous, differentiable nonlinear transfer functions with sigmoid shapes.

One of the most important characteristics of neural networks is that they can learn from their training experience.

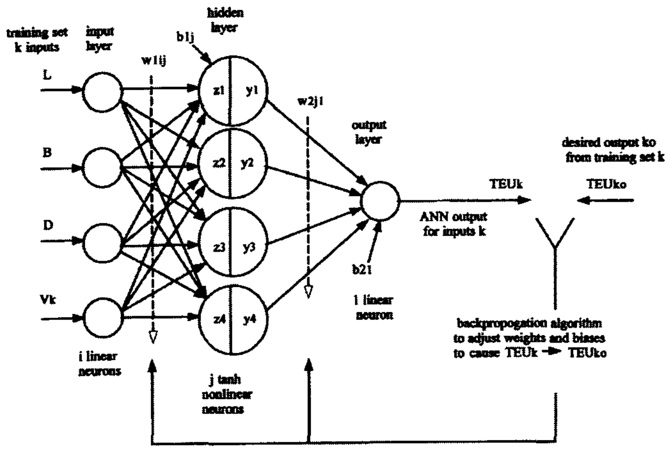

Figure 11.27 Schematic of (4x4x1) Feedforward Artificial Neural Network

Learning provides an adaptive capability that can extract nonlinear parametric relationships from the input and output vectors without the need for a mathematical theory or explicit modeling. Learning occurs during the process of weight and bias adjustment such that the outputs of the neural network for the selected training inputs match the corresponding training outputs in a minimum RMS error sense. Mer training, neural networks then have the capability to generalize; i.e., produce useful outputs from input patterns that they have never seen before. This is achieved by utilizing the information stored in the weights and biases to decode the new input patterns.

Theoretically, a feed forward neural network can approximate any complicated nonlinear relationship between input and output provided there are a large enough number of hidden layers containing a large enough number of nonlinear neurons. In practice, simple neural networks with a single hidden layer and a small number of neurons can be quite effective. Software packages, such as the MATLAB neural network toolbox (68), provide readily accessible neural network development capabilities.

11.5.3 Example Container Capacity Modeling

The development of parametric models using Multiple Linear Regression Analysis and Artificial Neural Networks will be illustrated through the development of models for the total (hull plus deck) TED container capacity of hatch covered cellular container vessel as a function of L, B, D, and V_K. A mostly 1990s dataset of 82 cellular container ships ranging from 205 to 6690 TED was used for this model development and testing. To allow a blind model evaluation using data not used in the model development, the data was separated into a training dataset of 67 vessels for the model development and a separate test dataset of 15 vessels for the final model evaluation and comparison. The modeling goal was to develop a generalized estimate of the total TED capacity for ships using the four input variables: L, B, D, and V_k.

The total TED capacity of a container ship will be related to the overall vessel size and the volume of the hull. Perhaps the most direct approach would be to estimate the total TED capacity using L, B, and D in meters as independent variables in a multiple linear regression model. This analysis was performed using the Data Analysis option in the Tools menu in Microsoft Excel to yield the equation:

$$TED = -2500.3 + 19.584\ LBP + 16.097\ B + 46.756\ D \quad [88]$$

(n = 67, R = 0.959, SE = 469.8 TED)

This is not a very successful result as seen by the Stadard Error in particular. Good practice should report n, R, and SE with any presented regression equations.

The container block is a volume so it would be reasonable to expect the total TED capacity to correlate strongly with hull volume, which can be represented by the metric Cubic Number (CN = LBD / 100). The relationship between the TED capacity and the Cubic Number for the training set is visualized using the Scatter Plot Chart option in Excel in Figure 11.28.

The two variables have a strong linear correlation so either a linear equation or a quadratic equation in CN could provide an effective model. Performing a linear regression analysis yields the equation:

$$TED = 142.7 + 0.02054\ CN \quad [89]$$

(n = 67, R = 0.988, SE = 254.9 TED)

which shows a much better Coefficient of Correlation R and Standard Error.

The vessel speed affects the engineroom size, which competes with containers within the hull volume, but could also lengthen the hull allowing more deck containers. It is, therefore, reasonable to try as independent variables CN and V_K to see if further improvement can be achieved. This regression model is as follows:

$$TED = -897.7 + 0.01790\ CN + 66.946\ V_k \quad [90]$$

(n = 67, R = 0.990, SE = 232.4 TED)

which shows a modest additional improvement in both R and SE.

Although the relationship between total TED capacity and CN is highly linear, it is still reasonable to investigate the value of including CN2 as a third independent variable. This multiple linear regression model is as follows:

$$TED = -1120.5 + 0.01464\ CN + 0.000000009557 CN2 + 86.844\ V_k \quad [91]$$

(n = 67, R = 0.990, SE = 229.1 TED)

which shows, as expected, a small coefficient for CN^2 and only a small additional improvement in SE.

To illustrate an alternative approach using simple design logic, the total TEU capacity could be postulated to depend upon the cargo box volume LeBD. Further, the ship could be modeled as the cargo box, the bow and stem portions, which are reasonably constant fractions of the ship length, and the engine room that has a length which varies as the speed V_k. This logic gives a cargo box length $L_e = L - aL - bV_k$ and a cargo box volume $L_eBD = (L - aL - bV_k)BD = (1 - a)LBD - bBDV_k$. Using these as the independent variables with CN in place of LBD yields the alternative regression equation:

$$TEU = 109.6 + 0.01870\ CN + 0.02173\ BDV_k \qquad [92]$$

(n = 67, R = 0.988, SE = 256.1 TED)

which is possibly not as effective as the prior two models primarily because the largest vessels today are able to carry containers both on top of the engine room and on the stem.

For comparison, a (4 x 4 x 1) neural network was developed by David J. Singer using inputs L, B, D, and V_k and output TED. The ANN has four linear neurons in the input layer, one hidden layer with four nonlinear hyperbolic tangent neurons, and a single linear neuron output layer. This neural network was trained with the MATLAB Neural Network Toolbox (68) using the 67 training container ships used to develop the linear regression models. This ANN design evaluated nets with 2, 4, 6, 8, and 10 hidden layer neurons with 4 giving the best results. The ANN was trained for 500 through 5000 epochs (training iterations) with 2500 giving the best results.

To evaluate the performance of the regression equations and neural network using data that was not used in their development, the final 15 test ships were used to test the neural network and the five regression equations presented above. They were compared in terms of their RMS relative error defined as:

$$RMS_i = \{\sum_{j=1}^{15} [(TEU_j - TEU_{ij})/TEU_j]^2/15\}^{1/2} \qquad [93]$$

where index i indicates the model and index **j** indicates the test dataset vessel. A summary of these results is shown in

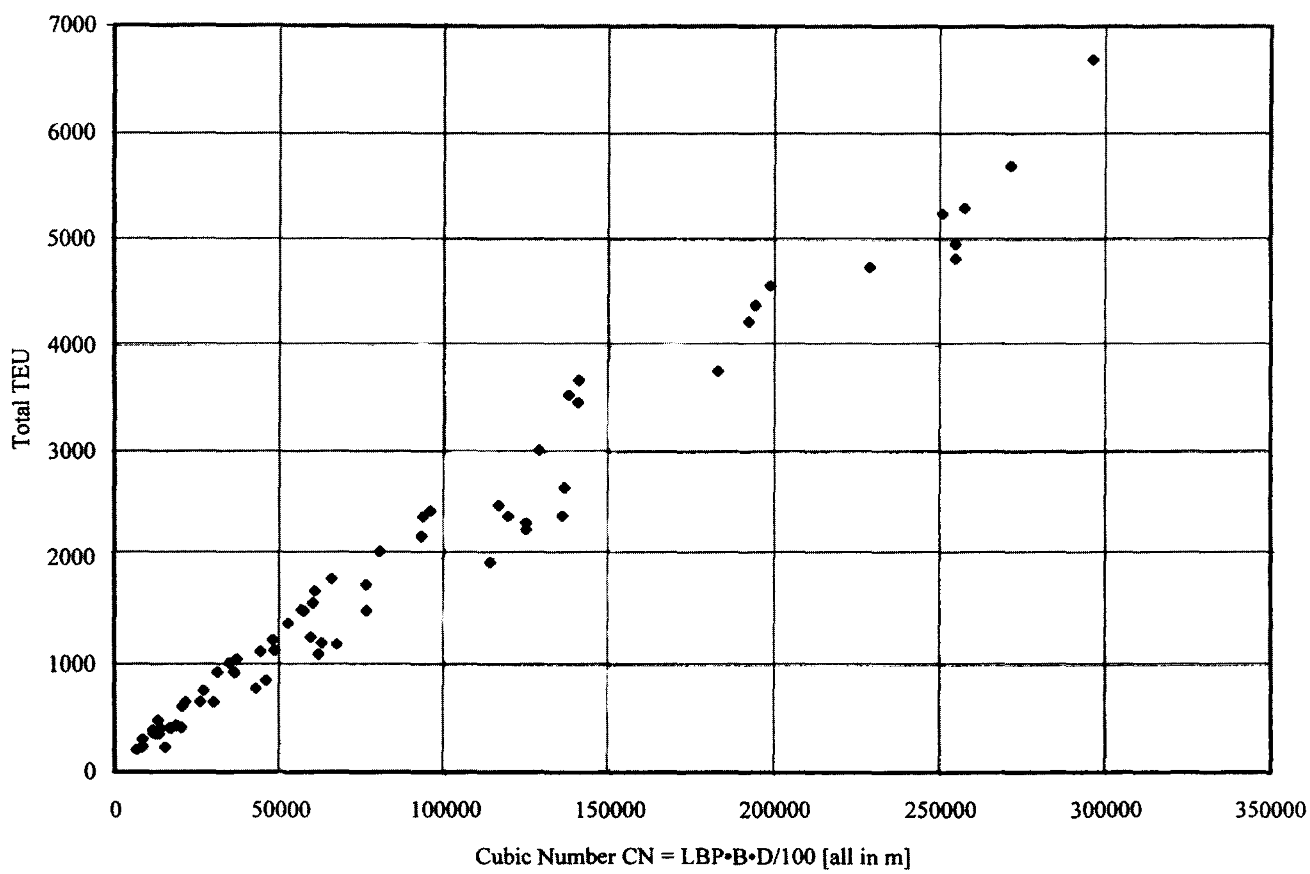

Figure 11.28 Total TEU Capacity versus Metric Cubic Number

Table 11.x. The most effective regression equation for this test data is equation 90, which had the highest R and nearly the lowest Standard Error. The ANN performed similarly. Note that for this highly linear example, as shown in Figure 11.28, the fulI capability of the nonlinear ANN is not being exploited.

11.6 PARAMETRIC MODEL OPTIMIZATION

The parametric models presented and developed in this chapter can be coupled with cost models and then optimized by various optimization methods for desired economic measure of merit and other cost functions. Methods currently available will be briefly outlined here.

11.6.1 Nonlinear Programming

Classical nonlinear programming methods were reviewed in Parsons (48). Nonlinear programming is usually used in early ship design with a scalar cost function such as the Required Freight Rate. A weighted sum cost function can be used to treat multiple objective problems by converting the multiple objectives fi(x) to a single scalar cost function. These methods can also be used to obtain a Min-Max solution for multicriterion problems.

The phrase Multi-discipline Optimization (MDO) is often used to apply to optimization problems involving various disciplinary considerations such as powering, seakeeping, stability, etc. Nonlinear programming applications in early ship design have done this for over 30 years. Note that MDO is not synonymous with the Multicriterion Optimization described below.

TABLE 11.X Maximum and RMS Relative Error for Regressions and ANN

Model	*Max. Relative Error*	*RMS Relative Error*
Regression Equations		
equation 88	0.771	0.3915
equation 89	0.088	0.1212
equation 90	0.037	0.0979
equation 91	0.059	0.1185
equation 92	0.069	0.1151
Artificial Neural Network		
ANN (4x4x1)	trained for 2500 epochs	0.123

The typical formulation for nonlinear programming optimization with λ objectives would be as follows:

Formulation:

$$\min_{\mathbf{x}} F = \sum_{i=1}^{\lambda} w_i f_i(\mathbf{x}) \qquad [94]$$

subject to

equality constraints	$h_j(\mathbf{x}) = 0,$	$j = 1,\ldots, m$
inequality constraints	$g_k(\mathbf{x}) \geq 0,$	$k = 1,\ldots, n$

with

fi(x) = cost or objective function i
Wi= weight on cost function i

This optimization problem can be solved by many numerical procedures available today. An example of the one of the most comprehensive packages is LMS OPTIMUS (69). It has a convenient user interface for problem definition and uses Sequential Quadratic Programming (SQP) for the numerical solution. Solver in Excel also has excellent capabilities.

Small design optimization problems such as that implemented in the Propeller Optimization Program (40) can utilize much simpler algorithms. In this particular example, the NeIder and Mead Simplex Search is used with the constrained problem converted to an equivalent unconstrained problem min P(x,r) using an external penalty function defined as:

$$P(\mathbf{x},r) = f(\mathbf{x}) - r \sum_{k=1}^{n} \min[g_k(\mathbf{x}), 0] \qquad [95]$$

where r is automatically adjusted by the code to yield an effective penalty (48). If the equality constraints can be solved explicitly or implicitly for one of the x_i this allows the number of unknowns to be reduced. Alternatively, an equality constraint can be replaced by two equivalent inequality constraints: h/x) ~ 0 and $h_{j+1}(x)$ ~ 0.

11.6.2 Multicriterion Optimization and Decision Making

In recent years, effort has been directed toward methods that can be applied to optimization problems with multiple criteria that can appear in marine design (70-72). In most cases this is a matter of formulation where issues previously treated as constraints are moved to become additional criteria to be optimized.

11.6.2.1 The analytical hierarchy process

There are a number of ship design optimization and design selection problems that can be structured in a hierarchy of influence and effects. The Analytical Hierarchy Process (AHP) introduced by Saaty (73) can be used to treat these problems. This method is well presented by Saaty (73) and Sen and Yang (72) and will not be presented further here. Marine applications are given by Hunt and Butman (74). AHP has also been used in ship design tradeoff studies to elicit relative values, see Singer et al (75).

11.6.2.2 Pareto and min-max optimization

The optimization with multiple criteria requires a careful definition of the optimum. The classical approach seeks a Pareto optimum in which no criterion can be further improved without degrading at least one of the other criteria. In general, this logic results in a set of optimum solutions. This situation is shown for a simple problem that seeks to maximize two criteria subject to inequality constraints in Figure 11.29. The figure shows the objective function space with axes for the two criteria f1(x) and fix). The feasible constrained region is also shown. The set of solutions that provides the Pareto Optimum is identified. At ends of this set are the two separate solutions f_1° and f_2° that individually optimize criteria one and two, respectively. Engineering design typically seeks a single result. The Min-Max solution provides a logical way to decide which solution from the Pareto optimum set to use.

A logical engineering solution for this situation is to use the one solution that has the same relative loss in each of the individual criteria relative to the value achievable considering that criterion alone f_{i°. The relative distance to the fj° are defined by the following:

$$z_i'(\mathbf{x}) = | f_i(\mathbf{x}) - f_i^\circ | / | f_i^\circ | \qquad [96]$$

$$z_i''(\mathbf{x}) = | f_i(\mathbf{x}) - f_i^\circ | / | f_i(\mathbf{x}) | \qquad [97]$$

where the first will govern for a minimized criterion and the latter will govern for a maximized criterion. The algorithm uses the maximum of the these two measures:

$$z_i(\mathbf{x}) = \max[z_i'(\mathbf{x}), z_i''(\mathbf{x})] \qquad [98]$$

The Min-Max optimum $y(\mathbf{x}^*)$ is then defined by the following expression:

$$y(\mathbf{x}^*) = \min_{\mathbf{x}} \max_{i} [z_i(\mathbf{x})] \qquad [99]$$

where the maximization is over the objective criteria i and the minimization is over the independent variable vector x. The resulting solution is shown in Figure 11.29. This solution will usually achieve any of the fj0, but is a compromise solution that has the same relative loss with respect to each of the fj° that bound the Pareto set. This yields a reasonable engineering compromise between the two competing criteria.

11.6.2.3 Goal programming

An alternative optimization formulation for multiple criterion problems is called goal programming (70-72,76). This approach treats multiple objective functions and sel~cted constraints as goals to be approached or met in the solution. There are two approaches for formulating these problems: Preemptive or Lexicographical goal programming and Archimedean goal programming. These two can be blended into the same formulation when this is advantageous (72).

Preemptive or Lexicographical goal programming solves the problem in stages. The solution is obtained for the first (most important) goal and then the problem is solved for the second goal with the added constraint that the first goal result cannot be degraded, etc. The process continues until all goals are treated or a single solution results. The approach restates the traditional objective functions as goals that are treated as additional equality constraints using positive slack or deviation variables $d_{k^\pm}$ defined to achieve the equalities. The cost function Z then involves deviation functions hj that are selected to produce the desired results relative to satisfying these goals.

Formulation:

$$\min Z = [P_1 h_1(d_1^-, d_1^+), P_2 h_2(d_2^-, d_2^+), \ldots, {}^{\mathbf{x}} P_{n+m} h_{n+m}(d_{n+m}^-, d_{n+m}^+)] \qquad [100]$$

subject to goal achievement

$$f_i(\mathbf{x}) + d_i^- - d_i^+ = b_i, \qquad i = 1, \ldots, n$$

and constraints

$$g_j(\mathbf{x}) + d_j^- - d_j^+ = 0, \qquad j = 1, \ldots, m$$

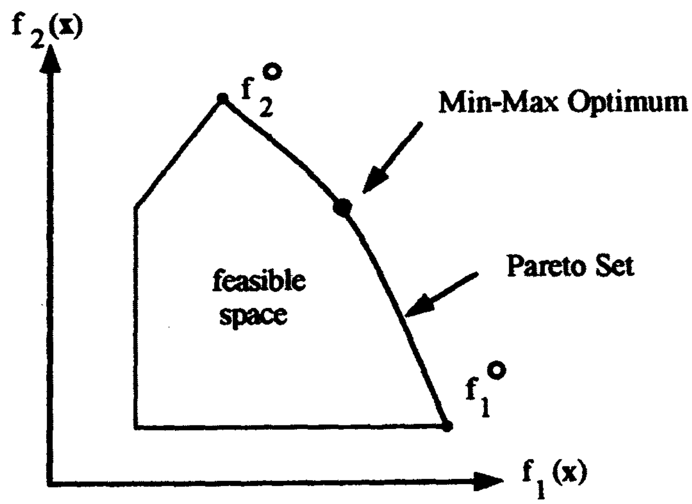

Figure 11.29 Illustration of Pareto and Min-Max Optima

with

$f_i(\mathbf{x})$ = goal i
b_i = target value for goal i
$g_j(\mathbf{x})$ = constraint j ≥ 0, ≤ 0, or = 0
d_k^- = underachievement of goal i or constraint j, k= i or n + j, $d_k^- \geq 0$
d_k^+ = overachievement of goal i or constraint j, k= i or n + j, $d_k^+ \geq 0$
P_i = priority for goal i achievement, $P_i >> P_{i+1}$

The priorities P_i are just symbolic meaning the solution for goal 1 is first, with the solution for goal 2 second subject to not degrading goal 1, etc. The numerical values for the P_i are not actually used. The deviation functions $h_i(d_i^-, d_i^+)$ are selected to achieve the desired optimization result, for example,

Form of h_i	Function
Goal /constraint reached exactly	
$h_i(d_i^-, d_i^+) = (d_i^- + d_i^+)$	(= b_i goal or = 0 constraint)
goal minimization/constraint approached from below	
$h_i(d_i^-, d_i^+) = (d_i^+)$	(min. toward b_i or ≤ 0 constraint)
goal maximization/constraint approached from above	
$h_i(d_i^-, d_i^+) = (d_i^-)$	(max. toward b_i or ≥ 0 constraint)

Archimedean goal programming solves the problem just a single time using a weighted sum of the deviation functions. Weights w_i reflect the relative importance and varying scales of the various goals or constraints. The deviation functions are defined in the same manner as in the Preemptive approach.

Formulation:

$$\min Z = [h_1(w_1^- d_1^-, w_1^+ d_1^+) + h_2(w_2^- d_2^-, w_2^+ d_2^+) \\ {}^x + \ldots + h_{n+m}(w_{n+m}^- d_{n+m}^-, w_{n+m}^+ d_{n+m}^+)] \qquad [101]$$

subject to goal achievement

$$f_i(\mathbf{x}) + d_i^- - d_i^+ = b_i, \qquad i = 1,\ldots, n$$

and constraints

$$g_j(\mathbf{x}) + d_j^- - d_j^+ = 0, \qquad j = 1,\ldots, m$$

with

$f_i(\mathbf{x})$ = goal i
b_i = target value for goal i
$g_j(\mathbf{x})$ = constraint j ≥ 0, ≤ 0, or = 0
d_i^- = underachievement of goal i or constraint j, k= i or n + j, $d_k^- \geq 0$
d_k^+ = overachievement of goal i or constraint j, k= i or n + j, $d_k^+ \geq 0$
$w_{k^\pm}$ = weights for goal i or constraint j, k = i or n + j, underachievement or overachievement deviations

In formulating these problems care must be taken to create a set of goals, which are not in conflict with one another so that a reasonable design solution can be obtained. Refer to Skwarek (77) where a published goal programming result from the marine literature is shown to be incorrect primarily due to a poorly formulated problem and ineffective optimization stopping.

11.6.3 Genetic Algorithms

The second area of recent development in design optimization involves genetic algorithms (GAs), which evolved out of John Holland's pioneering work (78) and Goldberg's engineering dissertation at the University of Michigan (79). These optimization algorithms typically include operations modeled after the natural biological processes of natural selection or survival, reproduction, and mutation. They are probabilistic and have the major advantage that they can have a very high probability oflocating the global optimum and not just one of the local optima in a problem. They can also treat a mixture of discrete and real variables easily. GAs operate on a population of potential solutions (also called individuals or chromosomes) at each iteration (generation) rather than evolve a single solution, as do most conventional methods. Constraints can be handled through a penalty function or applied directly within the genetic operations. These algorithms require significant computation, but this is much less important today with the dramatic advances in computing power. These methods have begun to be used in marine design problems including preliminary design (80), structural design (81), and the design of fuzzy decision models for aggregate ship order, second hand sale, and scrapping decisions (66,82).

In a GA, an initial population of individuals (chromosomes) is randomly generated in accordance with the underlying constraints and then each individual is evaluated for its fitness for survival. The definition of the fitness function can achieve either minimization or maximization as needed. The genetic operators work on the chromosomes within a generation to create the next, improved generation with a higher average fitness. Individuals with higher fitness for survival in one generation are more likely to survive and breed with each other to produce offspring with even better characteristics, whereas less fitted individuals will eventually die out. After a large number of generations, a globally optimal or near-optimal solution can generally be reached.

Three genetic operators are usually utilized in a genetic algorithm. These are selection, crossover, and mutation operators (66,79). The selection operator selects individuals from one generation to form the core of the next generation according to a set random selection scheme. Although random, the selection is biased toward better-fitted individuals so that they are more likely to be copied into the next generation. The crossover operator combines two randomly selected parent chromosomes to create two new offspring by interchanging or combining gene segments from the parents. The mutation operator provides a means to alter a randomly selected individual gene(s) of a randomly selected single chromosome to introduce new variability into the population.

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CHAPTER 12

Mass Properties

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12.1 INTRODUCTION

The use of the term *mass properties* by the shipbuilding industry when referring to the weight engineering process is now commonplace. In modem shipbuilding, *mass properties engineering* as a discipline encompasses all of the functions previously grouped under the more traditional generic term *weight estimating.* A variety of terms such as *weight engineering, weight control,* and others, continue to be used interchangeably with, and mean essentially the same as, *weight estimating* even though they are different. *Weight estimating* is the derivation of the weight of a ship during design whereas *weight control* is broader and includes the management of the weight of a ship during design and production. Similarly, the term *weight report* is routinely used interchangeably with the more generic term *weight estimate.*

However, the term *mass properties* is the appropriate term to use because by definition it includes technical aspects of moments, center of gravity, and other relevant physical and geometric properties of both individual parts and of the whole ship. Nevertheless, traditional terminology is still a part of the shipbuilding lexicon and as such for convenience has been retained in this text and is in various forms interspersed throughout the chapter. In this regard, any such use of traditional terminology should be interpreted as meaning mass properties in that the intent is to address not just weight, but weight and center of gravity, as well as mass moments of inertia.

Reliable initial determination and diligent oversight of a ship's mass properties are crucial to successful ship design and construction. The cumulative effect of a relatively small number of minor errors in the weight engineering process can lead to unsatisfactory ship performance and thus threaten a shipbuilding program. Major errors can at best cause serious delays and at worst could cause the program to be abandoned. The veracity of these statements is hard to question considering that each of the whole ship attributes in the following list is in some way dependent upon or influenced by the ship's weight and center of gravity:

- overall cost,
- hull proportions and lines,
- draft, trim and list,
- hull girder strength,
- reserve buoyancy
- intact and damage stability,
- dynamic stability,
- powering,
- maneuverability, and
- seakeeping.

Therefore, during the design process it is imperative that engineering personnel understand the contribution that their particular system makes in achieving acceptable overall ship design characteristics. Meeting weight and moment requirements for systems, components and equipment is as significant a requirement as any of the technical performance measurements that are used for other forms of design validation.

During the initial stage of design, the ship's weight, center of gravity, and with increasing frequency, radius of gyration (gyradius) are estimated either empirically or parametrically using data from earlier similar ship designs (see Chapter **11** - Parametric Ship Design). Adjustments are made to account for departures from typical features or to satisfy particular performance requirements. Hierarchical classification systems such as the U.S. Navy's *Expanded Ship Work Breakdown Structure* (ESWBS) (1), or the Maritime Administrations (MARAD) *Classification of Merchant Ship Weight's* (2), together with historical records from earlier similar ship designs facilitate the weight and moment estimating process by providing a detailed breakdown of the ship's functional systems in a convenient manageable format.

Reference material such as the Society of Allied Weight Engineers (SAWE) *Weight Engineering Handbook* (3) provides weight estimating methods for lightship and loads, as well an assortment of other useful information such as conversion tables, material properties and sectional properties of geometric shapes.

As the design progresses through its various stages, more reliable information becomes available in the form of schematics, diagrams, scantling plans, arrangement drawings, equipment lists, system sizes and layout, and now, more frequently, computer product models. Weight and center of gravity data are updated to reflect the development and availability of this more reliable information. When the design reaches an appropriate level of maturity a contract weight estimate is prepared as part of the contract package that is used for bidding purposes. Reliable weight and moment information is very important and according to D' Arcangelo (4) the effort needed to maintain quality data could be as much as 10% of the design budget. Though this percentage might be considered high today, shortchanging this effort none the less can lead to unanticipated inclining experiment results, which in turn can encumber the ship with undesirable operating restrictions. In addition, poor weight and moment control can cause cost increases or construction delays or both due to the design changes needed to recover weight or to adjust the position of the ship's center of gravity.

It is important for weight and center of gravity data to be checked to ensure that whole ship values are reasonable. Although not always possible due to budgetary constraints, independent validation by a separate agency, perhaps using an alternative estimating approach is highly desirable and recommended. Also, applying risk management techniques to the data is a strategy that is becoming increasingly popular, especially with military ships. Risk management involves assessing the probability of undesirable trends in weight growth and in the location of the ship's center of gravity occurring and identifying and evaluating appropriate risk mitigation options. The risk mitigation options may include such things as weight reduction initiatives or design changes that rearrange significant items of machinery or equipment. Clearly, all such risk mitigation options must be analyzed for impact on ship performance and also for impact on design and construction costs and schedul~s.

When the program reaches the detail design and construction stage it is normal practice to upgrade the weight and center of gravity data in the weight estimate with more reliable and more detailed information. Working drawings with comprehensive bills of material and more mature vendor information is developed during this phase and the information generated is available for use in refining the weight estimate. The increased use of three-dimensional product models capable of providing detailed information on individual piece parts together with relevant manufacturing information can provide a rich source of up-to-date weight information for upgrading the weight estimate. Design and engineering personnel, the customer, equipment and machinery vendors, suppliers of raw material, the shipyard's planning and construction departments and even the ship's crew can influence the ship's weight and center of gravity during detail design and construction. Each of these involved parties, especially the designers and engineers, can have a significant and directly measurable effect on the eventual total weight and center of gravity of the ship. Ships tend to grow in the wrong direction during design and construction. They inevitably get heavier and the vertical center of gravity has a tendency to creep ever higher. Given this tendency towards involuntary augmentation, it is incumbent upon all involved to be ever sensitive to whole ship mass properties needs and to resist the temptation to pad specific systems or components by making them more robust than they need to be. The opposite approach of underestimating the early weight estimates to suit the political goals of the marketing group or program manager must also be strongly resisted.

To help ensure that a successful ship is delivered to the customer, margins or allowances for acquisition are applied as a hedge against any propensity for weight and vertical center of gravity growth during design and construction. This tendency to grow continues throughout the ship's operationallife, a situation that must be considered during design by including a service life allowance. For commercial ships the issue of in-service growth is less significant than for military ships, especially combatants. This is because a commercial ship will generally spend its life in the trade it was designed for and not undergo extensive conversion. Also the maximum draft and thus displacement of the typical commercial ship is governed by its loadline assignment, and it is likely that if any major refits or conversions occur during its service life it would involve reclassification and a new loadline assignment. On the other hand, Navy surface combatants have very specific requirements for service life growth for both weight and vertical center of gravity.

During the course of the typical surface combatant's usefullife it is likely to experience several significant upgrades to its key systems. In addition to conversion and upgrades, experience has shown that naval ship weight and vertical center of gravity grows over its life due to unauthorized growth. In fact, substantial weight and vertical center of gravity increases have been observed in U.S. naval ships due to this unauthorized growth, not to authorized ship alterations. To accommodate this, the U.S. Navy requires the service life allowances specified in NAVSEA Instruction 9096.6B (5). It is important to note that available service life allowance at delivery is a key indicator of how well the ship meets contract requirements. This is why service life allowances must be monitored continuously and accounted for as an integral part of the mass properties engineering process.

Assigning acquisition margins or allowances during design and construction will not, in and of itself, ensure a satisfactory ship. The monitoring and reporting of acquisition margin consumption as design and construction progresses must be an integral part of an effective weight and center of gravity control program. This is undeniably true for military ships and although the actual process of weight and center of gravity control may be less stringent, it is true for commercial ships as well. The typical military shipbuilding program requires that the ship's weight and vertical, longitudinal, and transverse coordinates of the center of gravity be monitored and reported on throughout all stages of the design and construction process. Contractors involved in typical U.S. Navy new ship programs are in more and more cases resorting to the use of goal-setting techniques, technical performance measurements and trend charting as a means of preserving the ship's mass properties characteristics. Activities of this type support the early detection of undesirable trends, which in turn facilitates timely corrective action.

When the vessel is substantially complete, for both commercial and military vessels, an inclining experiment and deadweight survey is conducted that establishes the weight and vertical, longitudinal and transverse coordinates of the centers of gravity of the lightship. The inclining experiment and deadweight survey is described in detail in reference 6. The value in maintaining a reliable weight and center of gravity control process is readily apparent when the results of the inclining experiment and deadweight survey become available. Ideally, the values for lightship weight and center of gravity predicted by the weight control process will closely match those obtained by the inclining experiment and deadweight survey. This being the case, a high level of confidence can be placed in the final lightship values used to prepare the various delivery documents. By the same token, if there is a significant discrepancy but it can be shown that due diligence has been applied to the weight and center of gravity control process, appropriate steps can be taken to correlate the data in the most efficient way possible. High levels of confidence in the weight and center of gravity data will enable the decisions necessary for expedient resolution of the discrepancy. However, if oversight of the weight and center of gravity control process has been less than diligent, the resulting lack of confidence in the data could necessitate re-inclining the ship, which is both disruptive and costly. Clearly, the objective is to get good correlation. The best way to achieve this objective is to conduct both the design and construction weight control process and the inclining experiment with due care and diligence.

12.2 MANAGING MASS PROPERTIESDATA

When applied to a ship, the term *mass properties* refers to those physical characteristics that are defined by or derived from the magnitude, and distribution of the ship's weight. As such, mass properties include:

- weight,
- centers of gravity and moments,
- moments of inertia, and
- radius of gyration (gyradius).

In order to determine a ship's mass properties, every component of the ship must be accounted for, which represents a huge data management challenge. The weight and moment (mass properties) database is in effect a comprehensive listing of all of the components that constitute the complete ship. Each line item describes the component and locates it relative to a standard 3-axis orthogonal coordinate system. The database is organized by category and sub-category in a hierarchical system. There are many such systems in use throughout the world but in the U.S. either one of two commonly used classification systems is used. The United States Navy uses the *Expanded Ship Work Breakdown Structure* (ESWBS) (1), and commercial ships built in the U.S. typically use the Maritime Administration (MARAD) *Classification of Merchant Ship Weights* (2). The classification system categorizes each component according to type and sub-type and compiles the data according to a hierarchical numbering system. Table 12.1 shows the top-level ESWBS categories that are used for organizing database information. The ESWBS system manages the huge number of individual components in a mass properties database by assigning unique numbers at the component level, the system level and the ship level. In this way all components for a given sub-system define a system and several systems constitute a ship category. For example, ESWBS category I is **hull** structure, which breaks down into a number of structural systems such as *Decks and Platforms, Watertight Bulkheads* or *Foundations.*

Similarly, each system is broken down into a number of individual components such as *Plating,* and *Frames and Stiffeners.* **In** the ESWBS system, each component is assigned a five-digit number. The first three digits identify individual ship systems in a major one-digit category. For example, in the ESWBS element 622, the 6 identifies the item as part of an outfitting category, the first 2 identifies the component as being part of the **hull** compartmentation system and the second 2 identifies the item as being floor plating and gratings. The fourth digit in a five-digit ESWBS identifier is not normally used for weight accounting. The fifth digit identifies redundant systems within the three-digit group. For example, 62211 identifies floor plates and gratings inside the machinery space. ESWBS 62212 identifies floors and gratings outside of the machinery space.

Classification systems offer a convenient and reliable way to manage the huge amounts of data that comprises a typical mass properties database. Also, the permanent record created by the database classification method is a valuable source of information when developing initial weight and moment estimates for new ship programs.

Generally speaking, the MARAD classification system is functionally similar to ESWBS in that it offers the commercial shipbuilder a means for compiling, grouping and managing reliable weight and moment data. The main classifications for the MARAD system are shown in Table 12.11.

The two classification systems discussed here are representative of what is used routinely in the U.S. However, other classification systems do exist, an example being *Weight Classification for U.S. Navy Small Craft (7).*

Center of gravity, and the corresponding moments and inertia must be referenced to an established coordinate system. At present, there is no system universally used in the U.S. However, the Standard Coordinate System for Reporting Mass Properties of Surface Ships and Submarines (8) suggests an industry standard that should be considered.

The recommended coordinate system for U.S. ships mass properties data is shown in Figure 12.1. **It** originates at the intersection of the forward perpendicular (FP), the baseline (BL) and the centerline (CL) so that:

- the longitudinal center of gravity (LCG) is measured along the X-axis,
- the transverse center of gravity (TCG) is measured along the Y-axis, and
- the vertical center of gravity (VCG) is measured along the Z-axis.

The recommended sign convention is for the LCG to be positive for all items aft of the referenced origin; the VCG to be positive for items above the reference origin; and the TCG to be positive for all items on the port side of the centerline.

Rotational motion should be defined also in accordance with this same coordinate system as follows, but with the origin at the center of gravity of the ship:

- roll about the X- axis,
- pitch about the Y-axis, and
- yaw about the Z-axis.

Regular reporting of mass properties characteristics is a requirement for military programs. The content and presentation of these reports is in accordance with established formats. Acceptable weight report formats and types of weight estimates, reports and other useful information can be found in *Standard Guide for Weight Control Technical Requirements for Surface Ships* (9). The use of spreadsheet software is ideal for this type of periodic reporting in that the huge amount of data that constitutes a typical mass properties database can be conveniently and systematically managed and is easily updated.

12.3 MOMENT OF INERTIA AND GYRADIUS

The naval architect, when designing a commercial or naval ship, is concerned with ship motions. Accelerations due to ship motion can be severe enough to overstress the ship's structure, systems and payload and can also be hazardous to crew and passengers. Associated costs in terms of time and dollars from breakage and injury as well as from degraded performance of the crew can be significant. Also, severe motion can force ship operators to reduce speed and

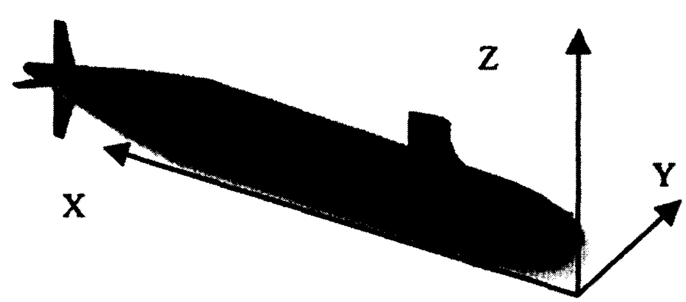

Figure 12.1 Isometric View of a Submarine Using the SAWE Recommended Coordinate System.

change direction, which again adversely affects operating costs.

A thorough discussion of the complex subject of ship motions is addressed in reference 6. Suffice to say, hull form, proportions, freeboard and natural periods of roll, pitch and yaw all influence the motion of a ship in a seaway.

Natural periods of roll, pitch and yaw, are each dependent upon the radius of gyration, or gyradius, about its associated axis. Depending on the availability of relevant information, values for gyradius can be approximated or calculated. Parametric approximation techniques exist that are reasonably accurate for similar ship types with similar geometries and stability characteristics. However, caution must be exercised when the stability characteristics, lightship weight or load distribution differ noticeably from that of the base ship. The preferred method for determining gyradius is by calculation using equations that show clearly the relationship between mass properties and ship motions. The equations for calculating gyradius relative to the conventional three-axis coordinate system are:

$$k_{roll} = \sqrt{Ixx / W}$$

$$k_{pitch} = \sqrt{Iyy / W}$$

$$k_{yaw} = \sqrt{Izz / W}$$

where

Ixx= weight moment of inertia of the ship in the roll direction

Iyy = weight moment of inertia of the ship in the pitch direction

Izz= weight moment of inertia of the ship in the yaw direction

W = total weight of ship

The weight moment of inertia in these equations is expressed in units of weight times length squared.

Cimino and Redmond (10) developed *rule-oj-thumb* values for the gyradius of different ship types, which are shown in Table 12.111.These rule-of-thumb values may be used in the early stages of design when lack of detail or system definition precludes more detailed analysis. However, care should be taken with these values when applying them to unconventional ships or hull forms. In these cases, it is recommended that some form of independent validation be used if available. A method for calculating the weight mo-

TABLE 12.I ESWBS Classification

ESWBS	*Description*
1	Hull Structure
2	Propulsion Plant
3	Electric Plant
4	Command & Surveillance
5	Auxiliary Systems
6	Outfitting Systems
7	Armament
M	Margins, Acquisition
F	Loads, Departure

TABLE 12.H MARAD Classification

MARAD Classification	*Description*
0–0 to 9–9	Hull Structure
10–0 to 19–9	Outfitting
20–0 to 29–9	Machinery

TABLE 12.III Estimated Gyradius Values

	Roll		*Pitch*		*Yaw*	
Ship Type	*% Beam*	*Tolerance (% Beam)*	*% Length*	*Tolerance (% Length)*	*% Length*	*Tolerance (% Length)*
Conventional Monohull	37.8	±1.5	24.9	± 0.4	24.8	± 0.4
Advanced Vehicles (LCAC)	39.4	± 5.7	27.2	± 3.3	29.1	± 3.8
SWATHs	43.5	± 0.1	29.7	± 1.5	31.8	± 1.7

Tolerance based on one standard deviation.

ment of inertia of a ship or a submarine is included in *Standard Coordinate System for Reporting Mass Properties of Suiface Ships and Submarines* (8), which was derived from Cimino and Redmond (10). Some ofthe more pertinent information from the SAWE document is duplicated in these pages as a convenience to the reader. However, it is recommended that users of this text avail themselves of the SAWE document, which is readily available on the SAWE web site at www.sawe.org/docs/rec_practlrp.html, and use it in conjunction with the material provided herein.

The data required for calculating the weight moment of inertia of a total ship is essentially the same as that contained in a typical weight estimate, with the exception of added mass due to entrained water which must be included when calculating the natural periods of ship motion. Therefore, as more detail and more reliable information becomes available and is incorporated into the weight estimate it follows that the weight moment of inertia calculation can be refined. However, one difference that must be respected that relates to the calculation of roll and yaw gyradius is the need to separate items that are identical port and starboard. Such items must be entered as separate database line items.

Reference 8 expresses the weight moment of inertia about the three rotational axes as:

Roll inertia

$$I_{xx} = I_{tx} + I_{ox}$$

or

$$I_{xx} \sum_n \left(w_n \left(y_n^2 + z_n^2\right)\right) \sum_n i_{ox_n}$$

Pitch inertia

$$I_{yy} = I_{ty} + I_{oy}$$

or

$$I_{yy} \sum_n \left(w_n \left(x_n^2 + z_n^2\right)\right) \sum_n i_{oy_n}$$

Yaw inertia

$$I_{zz} = I_{tz} + I_{oz}$$

or

$$I_{zz} \sum_n \left(w_n \left(x_n^2 + y_n^2\right)\right) \sum_n i_{oz_n}$$

where

I_{tx} = sum of the transference weight moments of inertia for all the elements about an axis parallel to the x axis through the ship's center of gravity

I_{ty} = sum of the transference weight moments of inertia for all the elements about the axis parallel to the y axis through the ship's center of gravity

I_{tz} = sum of the transference weight moments of inertia for all the elements about the axis parallel to the z axis through the ship's center of gravity \.

I_{ox} = sum of the item weight moments of inertia for all the elements about an axis parallel to the x axis

I_{oy} = sum of the item weight moments of inertia for all the elements about an axis parallel to the y axis

I_{oz} = sum of the item weight moments of inertia for all the elements about an axis parallel to the z axis

w_n = weight of the *nth* element

x_n = longitudinal distance of the *nth* element from the vessel's overall center of gravity to the item's center of gravity along the x axis

y_n = transverse distance of the *nth* element from the vessel's overall center of gravity to the item's center of gravity along the y axis

z_n = vertical distance of the *nth* element from the vessel's overall center of gravity to the item's center of gravity along the z axis

i_{ox_n} = weight moment of inertia of *nth* element about an axis parallel to the x axis and passing through the center of gravity of the *nth* element

i_{oy_n} = weight moment of inertia of *nth* element about an axis parallel to the y axis and passing through the center of gravity of the *nth* element

i_{oz_n} = weight moment of inertia of *nth* element about an axis parallel to the z axis and passing through the center of gravity of the *nth* element

A simplified representation for calculating the weight moment of inertia of a ship in the roll direction is shown in Figure 12.2. The item weight moment of inertia is calcu-

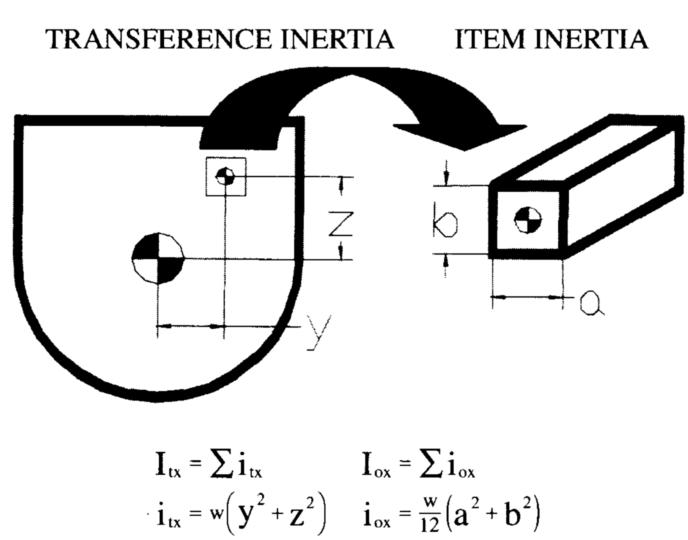

Figure 12.2 Elements for Calculating Roll Gyradius

lated assuming a homogeneous component of rectangular shape.

The accuracy of this method depends on the significance of the population of individual items used to calculate I_{ox}, I_{oy} or I_{oz}. Cimino and Redmond (10) predict that the accuracy of overall ship I_o would be within 0.5% of a full calculation if the population of individual items actually used includes all those that weigh 0.1% of the ship's displacement or greater.

During detail design and construction the weight and moment database should contain sufficient information to calculate I_o. However, during the early design stages when less detail is available, I_o can be approximated using the following equations.

For roll

$$I_{xx\,(proj)} = I_{tx} + (I_{ox\,(calc)} \times (W/W_c) - 0.175 \times I_{ox\,(calc)} \times (1 - (W_o/W))$$

For pitch

$$I_{yy\,(proj)} = I_{ty} + (I_{oy\,(calc)} \times (W/W_c))$$

For yaw

$$I_{zz\,(proj)} = I_{tz} + (I_{oz\,(calc)} \times (W/W_c))$$

where:

I_{proj} = total projected inertia
$I_{o(calc)}$ = sum of the item weight moments of inertia for all the elements
I_t = sum of the transference weight moments of inertia for all the elements
W_c = total weight of items used to calculate $I_{o\,(calc)}$
W = total weight of the ship

12.4 DETERMINATION OF COMPONENT WEIGHT AND CENTER OF GRAVITY

Determination of the ship's mass properties (weight and moment data) as design and construction progresses from stage to stage is an iterative process. Initial estimates compiled during concept design are usually derived from a combination of empirical data associated with earlier ships, parametrically generated data again using earlier similar ships as the model, the use of generic estimating formulae and, as often as not, educated guesswork by experienced mass properties personnel. As the design progresses, initial estimates are replaced with estimates from design documentation and available equipment weight.

After contract award, as the design matures, estimated values for component weight and center of gravity location are replaced at regular intervals with more reliable data. This upgraded information may be no more than a refined estimate. Most likely, though, it will have been derived by calculation using current engineering data. Some items may have been weighed. The weight and moment control process for the typical military program is highly structured with upgraded weight reports being prepared at regular intervals. Each subsequent iteration will see more and more of the estimated values for individual components and parts replaced with calculated, measured or weighed values. Properly conducted, the process will result in progressively more reliable whole ship mass properties data that will eventually correlate well with the inclining experiment and deadweight survey results and ideally represent a contractually compliant ship. Although less structured, a similar series of iterations aimed at keeping weight and moment data current should be utilized for commercial projects.

The level of effort required for an effective mass properties program is substantial. The line item count for relatively simple commercial ships such as tankers or bulk carriers can run into the thousands. For bigger highly complex military ships such as aircraft carriers, the number is in the tens or hundreds of thousands. Ultimately, the size and complexity of the ship, any special design requirements and the extent to which unconventional technologies have been used will influence the required level of effort. In the final analysis, the quality of the mass properties program will only be as good as the level of effort applied to it.

There is a variety of weight estimating and weight calculating methods in use throughout the industry. The methods most commonly used in the shipbuilding industry to determine component weights and centers of gravity are limited to:

- estimates using parametric or ratiocination techniques,
- estimates from initial design documentation, such as system diagrams, scantling plans, and preliminary arrangement drawings,
- calculations based on detailed construction drawings or product models,
- actual weighing using certified equipment,
- certified vendor data, or
- a combination of these.

Selection of the appropriate method requires careful consideration. The type of application, degree of complexity, available detail, and the time and cost needed to do the analysis are issues that need to be considered.

During the early stages of design when information is limited and budgets and schedules are usually tight, the use of simpler more empirical methods is appropriate (see Chapter 11 - Parametric Design). As the design develops and more information becomes available, more sophisticated techniques come into play (see Chapter 5 - Ship Design Process). The configuration of a particular item may be quite similar to a previous design in which case the use of parametric methods would be appropriate. Complex items with little or no design history to draw upon often require a more detailed method to achieve the desired degree of accuracy. Regardless of the method used, the mass properties engineer must determine which weight drivers are accounted for and which are not. Specific design requirements and the use of non-traditional technologies are either explicitly or implicitly accounted for by the estimating method itself. If a particular design criterion or the level of technological innovation is different from anything that is intrinsic to the calculation method, the impact of those differences must be taken into account.

Mass properties engineering during concept design relies to a large extent on the use of parametric methods that use similar objects or components as models from which to extrapolate the required data. Within the past two or three decades *ratiocination* techniques have been introduced to the mass properties engineering community. In addition to applying the basic principles of parametrics, ratiocination also brings certain elements of methodical and logical reasoning to the estimating process. The Society of Allied Weight Engineer's *Weight Engineers Handbook* (3) describes three different ratiocination techniques in terms of their application to individual weight classification groups according to their dependence upon the amount of reference material available. In using ratiocination techniques, as with other parametric methods, it is important to account for variations in design requirements and any technological differences between the model design and the new design.

Several attempts have been made to apply statistical methods to weight estimating during the early stages of design. An approach that utilizes standard empirical curve fitting routines to develop equations including standard deviation values is described in reference 11. Using the computer program, *Best-Fit*, Kern demonstrates how an array of statistical data consisting of fifty observations, each having a maximum of eight independent variables can be reduced to equations of the following form:

$$W = K \cdot V_1^{P1} \cdot V_2^{P2} \ldots V_8^{P8}$$

The program produces the factor K and exponents P from inputs of Wand V where W is weight as the dependent variable and V are independent variables, which are selected from the various ship parameters that are typically available very early in the design process. Independent variables include length overall, waterline length, beam, depth, draft, etc. Various combinations of these variables were tested in order to obtain the best-fit curve, that is, the least standard deviation. Kern demonstrated the effectiv~riess of the method experimentally by using it to prepare three partial weight group summaries for three ships. A comparison between the results obtained using the *Best-Fit* program and the actual Final Weight Report summaries served to validate the method. Kern concluded that this type of statistical method of estimating weights during early design is an acceptable alternative to ratiocination. Reference **11** is one example of how statistical methods can be used to improve weight estimating during the early stages of design. The system can also be used to estimate center of gravity data. However, statistical systems are dependent upon the availability of data for a suitable population of appropriate ships. The statistical data used by Kern was derived from fifteen U.S. Navy surface ships built over a period of fifteen years. It is possible that a reasonable database of commercial ship information could be accumulated in less time.

As design development progresses, more reliable information becomes available, which is incorporated into the mass properties database as a part of the iterative process discussed earlier in this section. More reliable information comes from a number of sources, examples of which include:

- enhanced, more complete system descriptions, diagrams and arrangement drawings,
- more complete bills of material,
- parts standardization,
- improved vendor information, and
- computer models.

As an example, during preliminary design the mass properties characteristics of a typical piping system would probably be derived parametrically. Subsequent development of the system diagram and ship arrangement drawings and then the detailed construction drawings will result in progressively more reliable information becoming available that can be inserted into the mass properties database as part of the iteration process. Unit weights for piping, fittings and equipment would typically be derived from vendor's catalogs, company standards, or historical records. These company standards and historical records typically reflect or reveal mill or casting tolerances, or weld and paint allowance factors. Fittings would include flanges, hangers, elbows, tees, couplings, gages and thermometers. In addition to valves, equipment includes strainers, freestanding tanks, air flasks, demineralizers, etc. In more progressive commercial shipyards, pipe details, fittings and equipment are for the most part captured in company design standards that in addition to material, configuration, and installation data also include weight and center of gravity information. Variables, such as pipe length and location and the number and location of hangers and fittings would be derived using the method most consistent with the maturity of the design, that is, parametrically in the early stages with calculated, measured or weighed values being inserted, as the information becomes available. Insulation weight would be based on the pipe length and the unit weight of the insulation material.

The use of finite element methods for analyzing structure and piping systems and the increasing use of 3-D product models for composite arrangements provides another useful source of information for the mass properties engineer. Generally speaking, these types of computer-generated data become available somewhat later in the process. Nevertheless, used properly, this information provides excellent validation of weight and moment data very quickly and easily and as such can be very useful. However, a note of caution to the user of this information is in order. Care must be taken to ensure that the computer models reflect the level of detail required for the recovery of realistic weight data. For example, finite element models, depending on the size of the model and the coarseness of the mesh, will often omit details like minor brackets, chocks, access openings and perhaps lightening holes. Similarly, the 3-D product model is unlikely to include such things as fasteners, paint, underlayment and other types of deck coverings. Therefore, when using such data it is important for the mass properties engineer to know what is and what is not included in the model.

12.5 MARGINS AND ALLOWANCES

Experience has shown that a ship regardless of type, size or complexity has a tendency to grow during design and construction. Inevitably it seems, the lightship weight will increase and the vertical center of gravity will climb. The longitudinal and transverse centers also will wander to some extent but the consequences of this happening are typically not as serious, although such situations should not be ignored. Acquisition margins are assigned early in the design process as a means of coping with these tendencies. The usual acquisition margin included in the contract weight estimate for commercial ships, such as tankers, general cargo ships, cargoliners and container ships is 3% of the lightship weight in conjunction with 0.3 m rise in vertical center of gravity.

Several margins are assigned to u.S. military ships that are referred to collectively as acquisition margins. These acquisition margins are described in reference 5 and consist of Preliminary and Contract Design Margins, Detail Design and Build Margins, Contract Modifications Margin, and Government Furnished Material Margin. NAVSEA considers the allocation of acquisition margins an essential element of ship design that mitigates risks associated with failure of the ship to meet the required mass properties characteristics at delivery. The NAVSEA margin allocation process accounts for historical patterns of weight and KG growth, unique ship features, injudicious application of margins and variations in acquisition strategy and policies.

In addition to acquisition margins, which as a general rule, are consumed prior to delivery, ships procured by the U.S. Navy must be delivered with an additional allowance in accordance with the requirements of reference 5. This additional allowance called the service life allowance (SLA) is intended to account for reasonable growth in weight and KG during the ship's service life without unacceptable compromise of the ship's principal naval architectural characteristics and performance. These weight and KG SLAs must be incorporated during the earliest stages of design and construction and must be continuously accounted for to ensure that they are available at delivery. The concept of a SLA is normally not applied to commercial ships. The displacement at which the commercial ship operates is governed by the loadline assignment. Typically, unless the ship is reclassified for some reason, the loadline won't change, which obviates the need for a weight service life allowance. If a commercial ship experiences an unexpected increase in lightship KG due to some form of modification, an inclining experiment and deadweight survey would be required and a new stability letter would be issued. The revised stability letter mayor may not involve new or modified operating restrictions.

An essential step that must occur during the early stages of design is the determination of the maximum permissible KG and the limiting draft, and, by association, the limiting displacement. These vitally important naval architectural characteristics are dependent upon hull form, watertight subdivision, compartmentation and intact and damaged stability. Once set, these characteristics are almost impossible to change without major disruption to the program. Figure 12.3 shows graphically how the four components of weight and KG, that is, lightship, loads, acquisition margins and service life allowance, constitute the total ship weight and KG. Figure 12.3 also illustrates the break out ofthe acquisition margin into four subcategories, which would be typical of a U.S. naval ship. It can be seen from Figure 12.3 that the combined weight and KG for the four weight components must not exceed the limiting whole ship values.

From this it follows that any growth in lightship, load or acquisition margin will result in a corresponding decrease in service life allowance. Should this situation occur it would almost certainly result in a contractually unsatisfactory ship at delivery.

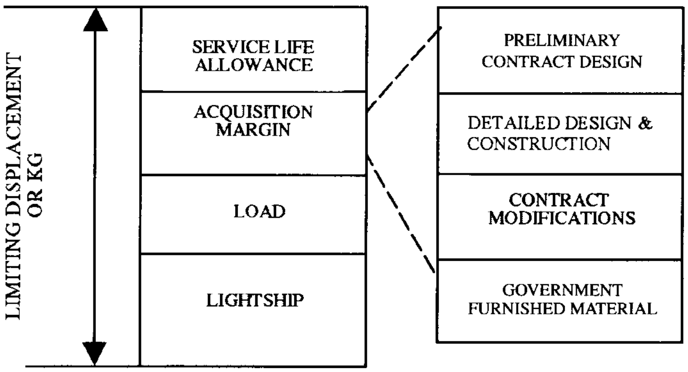

Figure 12.3 Constituents of Limiting Displacement and KG

The only means for recovering service life allowance would be to either take weight off of the ship or to make radical configuration changes to the ship that would increase the limiting values for draft and KG. Neither option is realistically feasible considering that this type of situation would almost certainly occur very late in the program. This situation serves to emphasize the importance of responsible mass properties management and a high quality initial weight estimate. Even though service life allowance is a device used after delivery to best serve the customer's needs it is inescapably the contractor's responsibility to ensure that the SLA required by contract is in fact available.

As previously discussed, acquisition margins provide a hedge against the tendency for growth in both the lightship weight and lightship vertical center of gravity during design and construction. An important aspect of mass properties management is the judicious and controlled consumption of these margins. In order to manage margin consumption mass properties personnel need to recognize situations that could result in growth in lightship weight or KG and as a consequence consume margin. Growth in lightship weight and KG occurs for a variety of reasons, examples of which are listed as follows:

- underestimated or overly optimistic initial estimates,
- undetected error accumulation,
- changes in the approach used to design certain systems,
- unregulated increases in the size and number of certain types of components,
- ship arrangement or configuration changes that are not a part of an adjudicated contract change,
- unexpected development problems that are not a part of an adjudicated contract change,
- change in customer requirements that are part of an adjudicated contract change,
- overly demanding schedules that place constraints on the design optimization process,
- equipment model changes,
- material substitution, and
- actual tolerances in raw material such as steel ana pipe.

Generally speaking these potential margin-consuming situations are at least to some extent manageable. However, there are situations and unauthorized departures from construction drawings that are almost impossible to manage. The prudent mass properties engineer should try to recognize these situations and take appropriate steps.

As noted earlier, design margins for commercial ships usually follow the essentially empirical values of 3% of lightship weight and 0.3 m for KG. However, the process by which acquisition margins for military programs are established is much different. NAVSEA Instruction 9096.6B (5) provides ranges for each of the margin types discussed earlier in this section. These ranges are presented in Table 12.IY. The actual values used in the mass properties process are usually arrived at through negotiation between the contractor and the customer. The negotiations traditionally revolve around the accepted weight estimate, which is the document that defines the not-to-exceed characteristics of the ship at delivery. The contractor will negotiate in terms of what he is best capable of achieving; the customer from the position of what he wants to see in the delivered product. Both sides of the negotiation will utilize risk assessment tools to support their objectives. The contractor's past performance will also playa significant role in this process.

Under the U.S. Navy's acquisition reform strategy, the traditional program phases (Preliminary Design, Contract Design, and Detail Design/Construction) have been replaced with a time line approach that is geared to key program milestones. The differences between the two approaches will have an impact on the margin selection ranges shown in Table 12.V necessitating changes that will be reflected in subsequent revisions to reference 5. Generally speaking, it is safe to say that actual margins will reflect the level of inherent risk associated with specific programs. Also, under acquisition reform, the contractor is performing early stage design and now derives acquisition margin as early as the conceptual design stage.

SLA requirements for U.S. Navy ships are predetermined in the contract language. In most cases SLAs will be in accordance with the requirements of reference 5. Exceptions would be on a case-by-case basis.

As previously alluded to, risks associated with design and construction are important considerations when establishing acquisition margin values. Multiple risk areas must be assessed and their combined impact captured in a single margin value, which is a difficult undertaking requiring considerable care. Typically, margin consumption is reviewed periodically to ensure that remaining margin is consistent with known residual risks. During the early stages of design, the review is based on one-digit ESWBS weight categories, during later stages on the three-digit level. Risk surveys of the type discussed by Redmond (12) are useful when setting margin values. Basically the method rates average risk values according to a scale of 0-10 creating a factor that is applied to the margin ranges shown in Table 12.V. Additional material on the subject of margins and allowances can be found in reference 13 and also at the SAWE website: www.sawe.org/docs/rec_pract/rp.html.

12.6 MASS PROPERTIES MANAGEMENT

If design and construction issues are resolved on the strength of decisions that do not fully consider the ship's weight and moment characteristics, a likely consequence will be unsatisfactory mass properties characteristics.

Effective mass properties control in accordance with a defined management plan is invoked as a matter of policy on most military programs. Cost and schedule constraints tend to limit the extent to which similar practices are employed on commercial projects. Nevertheless, the prudent commercial ship builder will employ some form of management control.

In order to ensure that weight and center of gravity issues are properly considered during new construction programs, the U.S. Navy typically requires that the contractor prepare a weight control plan that includes coverage of the management methods to be used. References 9 and 14 provide useful guidance on the development of a weight control plan.

The following list of recommendations for achieving successful mass properties control is extracted verbatim from reference 15. The author, F. Johnson, believes that the key techniques and requirements for a successful mass properties control program are:

1. an accurate and timely weight and balance status that projects trends,
2. knowledge of the design conditions that are driving the weight and the requirements that cause them,
3. a cadre of innovative conceptual design engineers and technologists,
4. a management team that sets priorities, makes timely decisions, is accessible, and is willing to take acceptable risks,
5. an informed customer with leadership that wants to be part of the design team instead of a specification policeman, sets priorities among its own specialties and is willing to accept specification trades,
6. open communication between the customer and company technical specialists,

TABLE 12.IV Service Life Allowances for U.S. Navy Surface Ships

	Weight %[1]	*KG*[2] *Feet*
Combatants	10.0	1.0
Carriers and Large Deck Amphibious Warfare	7.5	2.5
Other Amphibious Warfare	5.0	1.0
Auxiliary	5.0	0.5
Special Ships and Craft	5.0	0.5

1. Weight percentage based on the predicted full load departure displacement at delivery.
2. KG values based on the predicted full load departure KG at delivery.

TABLE 12.V U.S. Navy Acquisition Margin Selection Ranges

	MARGIN			
	Weight – Percent of Lightship		*KG – Percent of Lightship*	
Acquisition Phase	*Minimum*	*Maximum*	*Minimum*	*Maximum*
Preliminary/Contract Design	0.8	4.4	2.7	6.1
Detail Design and Construction	4.5	9.8	1.7	5.1
Contract Modifications	0.4	2.1	0.9	1.9
Government Furnished Material	0.2	0.7	0.1	0.4

7. rapid identification of potential weight and balance trends,
8. informal goal setting and monitoring,
9. an assertive mass properties control plan supported by management,
10. sub-contractor control,
11. adequate staffing of skilled engineers and a schedule that allows for design iteration,
12. mass properties control down to the engineering job level, and
13. flexibility of approach.

Although this list emanates from the aerospace industry, it is readily applicable to shipbuilding where adherence to these thirteen techniques and requirements could be of help when striving to conduct an effective mass properties control program.

Overall responsibility for weight control is usually assigned to a Mass Properties Manager whose functions traditionally include the following:

- develop, compile and maintain the weight and moment database,
- develop and administer periodic weight reports,
- coordinate the weight control feedback system, and
- oversee and coordinate the weighing program.

In May 1995, the U.S. Secretary of Defense directed the implementation of Integrated ProductJProcess Development (IPPD) throughout the Department of Defense acquisition process. IPPD is a management methodology that incorporates a systematic approach to the early integration and concurrent application of all the disciplines that playa crucial role throughout the life cycle of a system. This process seeks to use multi-disciplinary teams known as Integrated Product Teams (IPT) to optimize the design, manufacture and support of a system through the application of quality and system engineering tools and by utilizing industry best practices. In this regard, the U.S. Navy's acquisition reform strategy has bestowed an additional function on the mass properties manager, which is to head a Mass Properties Control IPT. Employing the IPPD management methodology is a requirement for U.S. military programs. No such requirement exists for commercial projects. However, adopting some means of sharing the responsibility for mass properties between the key design and construction disciplines and the owner is recommended. In the world of military shipbuilding, the Mass Properties IPT will identify design constraints, set weight and center of gravity goals and support individual system goals to help achieve overall whole ship goals. Technical Performance Measurement (TPM) techniques are used to assess the effectiveness of the mass properties control effort. Typically, the IPT will conduct periodic evaluations of the TPM results to establish the overall status of the program. The IPT findings serve to keep individual system owners apprised of the mass properties characteristics of their particular system and to alert the appropriate program personnel when there is a demonstrated need to pursue initiatives for reducing weight or KG or both.

The IPT will allocate specific and achievable weight and/or KG goals for each functional group or system. The exact methodology of how the allocation is determined would be decided by the IPT. An objective is to make this allocation a goal that is reasonable and therefore, achievable. The groups assigned a weight target will be required to meet that goal as they would any other design requirement. The work on the component or system will not be considered complete unless the assigned weight goal has been met as well.

In some cases it is reasonable for sub-contractors and vendors to be invited to participate in the activities of the Mass Properties IPT. Sub-contractors and equipment vendors also should be allocated mass properties goals. Whenever possible, throughout the design process, sub-contractor and vendor performance should be monitored to ensure their projected final weight values will be met. The shipbuilder's procurement documentation should require vendors and sub-contractors to provide calculated weight, scaled weight, and center of gravity information according to a defined mutually agreed to schedule.

For both commercial and military projects the mass properties control process begins once a Baseline Weight Estimate (BWE) has been established. The BWE serves as the starting point in a design phase for comparative analysis with subsequent estimates. Once a detail design and construction contract is awarded, the key U.S. Navy document that defines the agreed upon values for the ship's mass properties characteristics is the Accepted Weight Estimate (AWE) or Allocated Baseline Weight Estimate (ABWE).

These weight estimate reports establish weight and vertical, longitudinal and transverse center of gravity locations with and without acquisition margins for the lightship and for selected conditions of loading. Reference 14 includes definitions of these weight estimate reports, lightship and of the various loading conditions. The weight estimate reports also include load summary sheets that show the ship's basic naval architectural characteristics such as drafts, displacement, trim and list for each loading condition specified by the contract. The AWE or ABWE, besides being the documents of record for identifying the agreed initial acquisition margins, also records initial service life allowance predictions either by establishing not-to-exceed values for weight and KG or by stating actual weight and KG service life allowance values. The equivalent process for commercial programs is usually less formalized than what has just been described for military ships. Nevertheless, it is aimed at achieving similar levels of understanding between contractor and customer relative to oversight of the ship's mass properties characteristics.

The mass properties control process required for U.S. Navy programs is highly structured and involves significant management effort. During the design and construction phases, the baseline mass properties data is continuously and progressively refined and updated until the initial estimated value for each line item has been replaced with more reliable data. Refinements include better estimates, calculated and measured values and whenever possible data from actual weighings. This process is tracked over time with the fluctuations in whole ship characteristics resulting from the mass properties control effort being regularly reported to the customer via quarterly weight reports or QWRs. The format and content of the QWR is essentially the same as the weight estimate reports described earlier. Each QWR includes the current summary status of the acquisition margins in terms of how much has been consumed and hence how much remains. Tracking this particular element of the QWR over time can identify trends in acquisition margin consumption, which in turn can show the mass properties management team whether remedial action is or is not required. For example, undesirable trends would be a warning that acquisition margins are being consumed too quickly and as a result service life allowances may be in jeopardy. On the other hand, a desirable trend would tell management that mass properties control techniques currently in use have so far been effective or that initiatives instituted to recover either weight or KG margin appear to be having the desired effect. Figure 12.4 is a simplistic representation of how, over the ship's life, the acquisition margins are consumed during design and construction leaving the service life allowance for consumption after delivery. The shape of the acquisition margin portion of the curve could be indicative of the occurrence of an unfavorable trend that has been successfully compensated for by an offsetting weight reduction initiative leaving the SLA intact at delivery.

Obviously, if an undesirable trend develops late in a program the cost and schedule impacts from any remedial action cannot be avoided and must be factored into management's decisions. As a general rule the earlier an undesirable trend is detected the less the disruption will be to cost and schedule.

The management process can maintain oversight of the residual level of risk and uncertainty by evaluating the maturity of the mass properties information contained in the current QWR.

By determining the percentage of the overall mass properties database that is based on a specific estimating or engineering method and assigning a confidence level to each method, a sense of the overall maturity of the mass properties database can be established. The concept is best illustrated by an example. Figure 12.5 shows a pie-chart presentation of the breakdown by method for a typical mass properties database where each slice of the pie represents

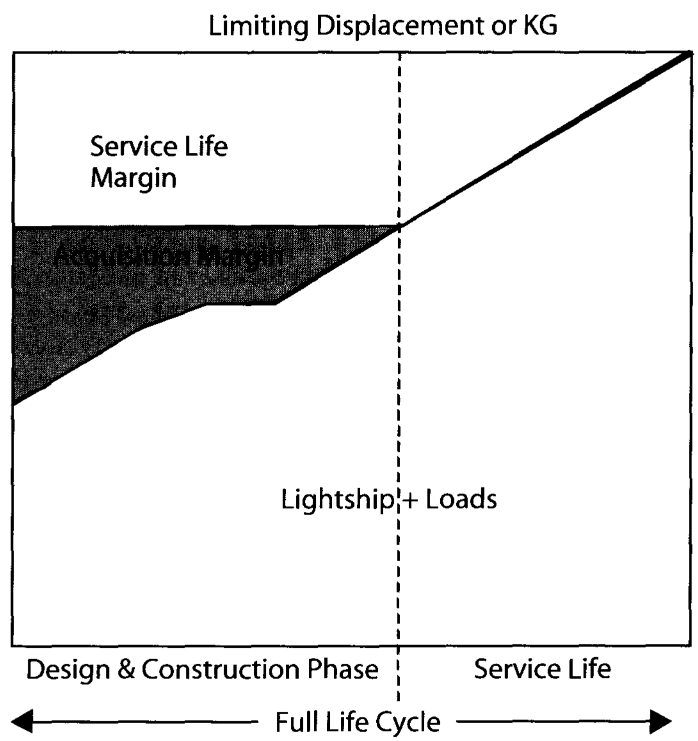

Figure 12.4 Margin and SLA Depletion

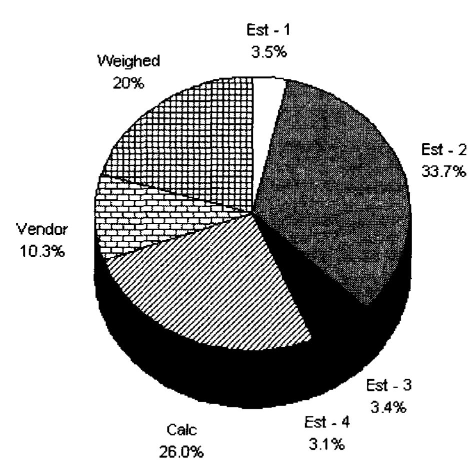

Figure 12.5 Weight Report Maturity

the percentage of the whole that has been determined using one of the following methods:

Est-l = Ratiocination from a similar ship,
Est-2 = Engineering estimate based on system descriptions and engineering specifications,
Est-3 = Estimate based on system diagram, scantling drawing or similar information,
Est-4 = Based on final preliminary design products, such as completed system arrangements or preliminary product models.
Calc = Based on detailed construction drawings or computer product model
Vendor = From certified vendor-supplied information
Weighed = From actual weighing of component or unit using certified weighing equipment.

The reliability of the methods range from low to high, with ratiocination being at the low end and methods based on calculation and weighing at the high end. Therefore, it follows that the distribution of methods is an indicator of the level of maturity of current mass properties data.

Big high reliability slices and small low reliability slices indicate higher degrees of maturity which, when correlated with the status of the acquisition margins, can be used to assess the overall state of ship's mass properties characteristics in terms of acceptability and residual risk. Routine database management techniques can be used to determine the percentages by assigning a unique flag to each method so that the system can use it to calculate percentages.

The same approach can be used to track the weight and KG performance of specific major components or systems.

Systems or components that due to their size and complexity could seriously impact whole ship mass properties must be considered high risk. This is especially true when substantial design development that must be accomplished in parallel with whole ship design remains to be completed. In situations like this it is normal to set weight and center of gravity goals that will help guide the system designer's decision-making process, and also help to enhance the oversight capabilities of the mass properties manager.

As an example, a typical computer-based monitoring system could produce graphical data that would track the mass properties characteristics of a major component or system over time relative to the assigned goals. The system also could assess the overall quality of the data by tracking the percentage of calculated versus estimated data. Figure 12.6 is an example of a typical tracking curve that shows system weight and percentage calculated over time.

Electronic tracking is a valuable management tool that provides all the information needed to continuously assess the quality of mass properties data and to identify trends. Such capabilities significantly improve the overall quality and hence reliability of the mass properties process.

The limiting values assigned to draft (and hencedisplacement) and KG as a result of the design process must be adhered to rigidly. Both characteristics are inextricably linked to the magnitude and distribution of ship weight. Even with the most careful oversight from everyone involved it is likely that at some point in the design process there will be a need to reduce weight, or to redistribute weight in order to reduce the KG.

The difficulty is identifying those candidates that have the highest level of compatibility with the overall program goals and objectives. In addition to design and construction goals the overall program usually sets performance goals relative to budgets, schedules and quality, which must be considered when strategizing a weight or KG reduction initiative.

When overall program goals have been set and prioritized, the individual weight and KG reduction initiatives can be evaluated for compatibility with them and the results of the evaluation can be used as a basis for selecting which of the initiatives to implement.

The success of any design and construction project depends in large part on how well the program goals are met. Program goals are typically concerned with achieving design and construction schedules, managing construction costs and engineering man-hours, and preserving key product characteristics such as the ship's performance which is influenced by lightship weight, lightship KG, list, trim, intact stability, etc. Accordingly, a system is required that is capable of evaluating how well a reduction initiative satisfies a wide range of goals, which in turn requires a system that can prioritize the program goals relative to each other.

The *Analytical Hierarchy Process* (AHP), which is described in reference 16, is an example of just such a system (see Chapter 5). AHP is a proven method that prioritizes goals through the use of pair-wise comparisons. It derives priorities in terms of percentages that indicate the relative value of each of the ship attributes evaluated. Because the AHP uses ratio scaling in its calculations, it provides more reliable data than other methods. An application of AHP to a ship design is described in reference 17. Menna demonstrates how results for goal prioritization might look something like those shown in Figure 12.7.

After project goals have been identified and prioritized, the degree to which each candidate weight or KG reduction initiative contributes to achieving those goals must be assessed. Organizing each of the candidates in a matrix and recording their relative scores against each goal as shown in Figure 12.8 provides an overall indicator of how well the candidate contributes to optimum whole ship design ob-

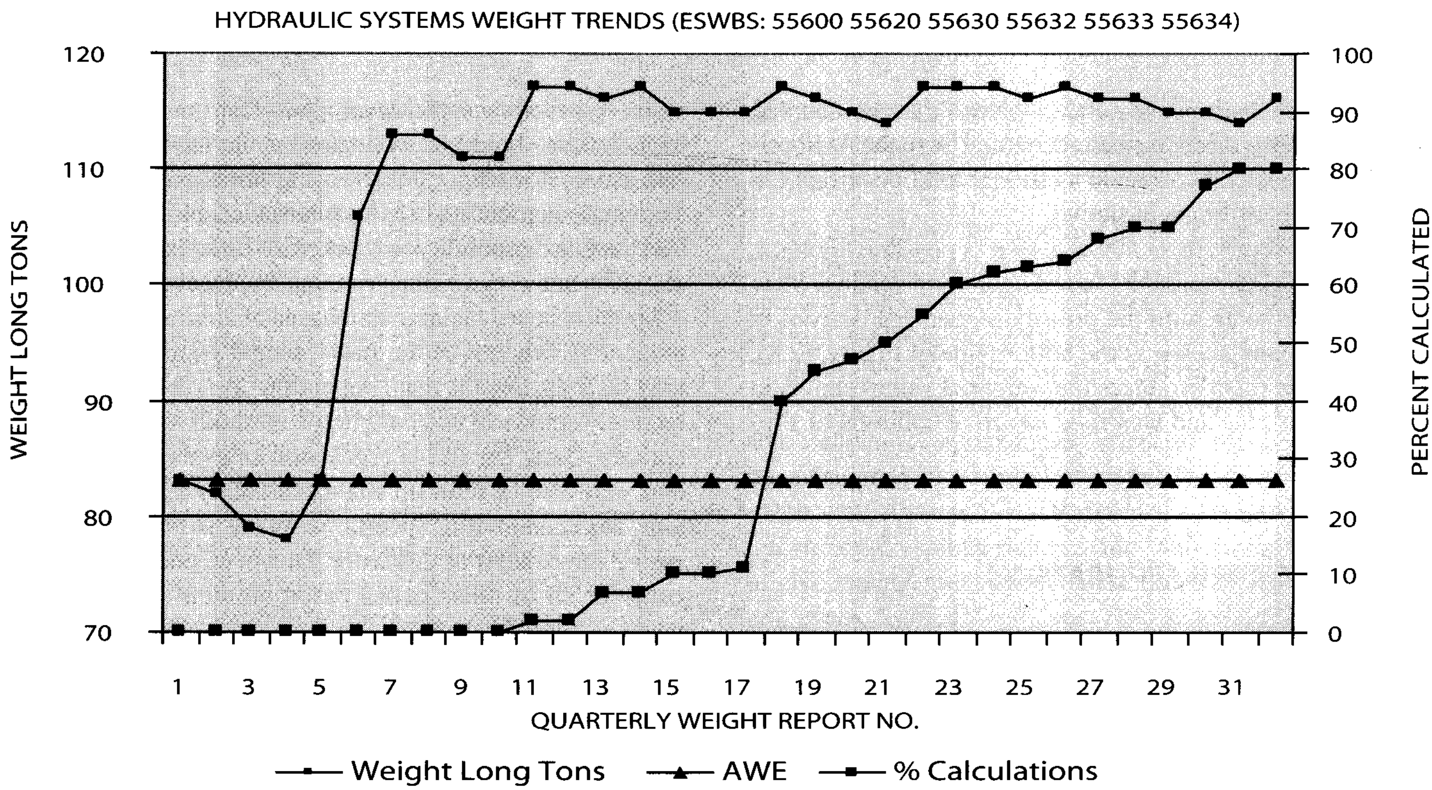

Figure 12.6 Typical Trent Tracking Chart

Criterion			Value
If row entry is	EQUALLY	as important as column entry	1
If row entry is	MODERATELY	more important than column entry	3
If row entry is	STRONGLY	more important than column entry	5
If row entry is	VERY STRONGLY	more important than column entry	7
If row entry is	EXTREMELY	more important than column entry	9

NOTE: If column entry is more important than row, then use the inverse of the above values.

	Construction Schedule	Manufacturing Cost	Engineering M anhours	Weight	KG	Seakeeping	Norm alized Sum s	Priority Percentage
Construction Schedule	1	3	3	1/3	1/3	7	1.15	19%
Manufacturing Cost	1/3	1	1	1/3	1/3	5	0.62	10%
Engineering M anhours	1/3	1	1	1/3	1/3	3	0.54	9%
Weight	3	3	3	1	3	5	2.08	35%
KG	3	3	3	1/3	1	3	1.36	23%
Seakeeping	1/9	1/5	1/3	1/5	1/3	1	0.25	4%
Totals	7.8	11.2	11.3	2.5	5.3	24.0	6.00	100%

Figure 12.7 AHP of Organizational/Project Goals

Effect on Priority	Value
Most Favorable	+ 9
More Favorable	+ 3
Favorable	+ 1
None	
Unfavorable	- 1
More Unfavorable	- 3
Most Unfavorable	- 9

	Construction Schedule	Manufacturing Cost	Engineering Manhours	Weight	KG	Seakeeping	Weighted Plus	Weighted Negative	**Value**
Candidate A	+ 9	+ 9	-1	+ 3	+ 1		3.9	-0.1	3.8
Candidate B	-1	+ 3		+ 9	+ 9	+ 3	5.3	-0.2	5.1
Candidate C	-1	+ 3	+ 9		+ 1		1.3	-0.2	1.1
Candidate D	+ 3	+ 3		-1	+ 9	-1	2.9	-0.4	2.5
Candidate E	+ 1			+ 1	-9	+ 9	0.9	-2.0	-1.1
Candidate F		-3	+ 3	+ 9	-3		3.4	-1.0	2.4
Candidate G	+ 3		-9	-1	+ 9	+ 1	2.3	-0.8	1.5
Candidate H	+ 9	+ 3	+ 1		+ 9	+ 1	4.2	0.0	4.2
Priority Percentage	19%	10%	9%	35%	23%	4%			

Figure 12.8 Matrix of Candidates and Associated Values

jectives. Each optimization indicator can then be coupled with its relative prioritization percentage from the AHP pri0ritization matrix to compute a rational total prioritization value for the candidate initiative.

By using scores of -9 through +9 it is possible to objectively assess each candidate based upon ratio scaling. Multiplying each score with the priority percentage derived in Figure 12.7 (and shown as the bottom line of Figure 12.8), and summing them produces the weighted values shown in the *weighted plus* and *weighted negative* columns of Figure 12.8.

12. 7 COMPUTER APPLICATIONS

The requirements of the typical mass properties program and the capabilities of the computer are an almost perfect match. Managing vast amounts of alphanumeric data and processing huge numbers of highly repetitious arithmetic functions is what the computer does best. This innate compatibility was recognized soon after the appearance of the first mainframe machines and shipyards and design firms began developing proprietary weight engineering software. Over time, these early, rudimentary products have evolved into highly sophisticated full management systems mounted on desktop networks. Some indications of the trends in mass properties engineering as it is being conducted in today's ship building environment are described in, references 18 and 19.

Modem systems increase the efficiency with which the mass properties process is accomplished and significantly improve the reliability of the data generated. Estimates, calculations and reporting are all enhanced as a result of computerization. The typical full service modern system is capable of most if not all of the following:

- producing initial estimates using empirical and parametric methods,
- analyzing the mass property characteristics of individual parts, systems and the total ship,
- generating a full range of reports in appropriate formats and classifications,
- producing system or product structured reports,
- developing weight distribution curves,
- calculating the inertia and gyradius of individual parts, systems and the total ship,
- performing uncertainty analyses,
- performance measurement, and
- material forecasting.

The strengths and weaknesses of available software systems tend to vary depending on the circumstances that prevailed when they were developed. The relative merits of each system should be evaluated on the basis of the built-in features it incorporates. Some systems emphasize database management and report generation more than others and have the capability to work with different hierarchical classification codes. Other systems emphasize initial weight estimation based on large databases of similar ships or systems. The strength of the basic weight estimating routine may be a significant issue depending as it does on how effectively empirical and parametric methods are used to generate the data. The use of regression analysis and statistical data may also be relevant when evaluating a particular system. Recommending specific software is not appropriate within the context of this work. However, end users should consider all of these issues based on their specific needs when making a selection.

Modem three-dimensional product modeling systems often can provide weight and center of gravity information at the component, system and total ship level very quickly. A design synthesis program, of this type, that contains a mass properties module can, when used carefully, be of considerable benefit to the weight control engineer. The calculation of weight and center of gravity data for components and systems is virtually a push-button proposition. However, considerable care is required to ensure that the data extracted from the system is complete. The weight and moment data produced by the system can only reflect the condition of the model. Therefore, steps must be taken to ensure that preliminary information isn't mistakenly used and that whenever applicable, allowances are made for such items as:

- weld material,
- mill tolerances or casting allowances,
- fasteners,
- surface treatments (such as paint, insulation or deck underlayment),
- system liquids,
- loads such as tank liquids, and
- missing items (components not yet modeled).

The development and consistent use of standard operating procedures is strongly recommended as a way of minimizing risks of this type.

12.8 RISK AND RISK MANAGEMENT

Identifying and managing risk is another practice that has been promoted by the U.S. DoD acquisition reform strategy.

Although, consideration of risk and uncertainty in the design and manufacture of military and commercial systems is not in itself a new concept, the degree of focus now directed at this aspect of the acquisition process is much greater than ever before. A direct quote from the president of the Defense Acquisition University (DAU) serves to explain why this is so. Part of the DAU president's preamble to DoD Publication Risk Management Guide for DoD Acquisition (20) states:

> Acquisition reform has changed the way the Department of Defense (DoD) designs, develops, manufacturers, and supports systems. Our technical, business, and management approach for acquiring and operating systems has, and continues to, evolve. For example, we can no longer rely on military specifications and standards to define and control how our developers design, build, and support our new systems. Today we use commercial hardware and software, promote open systems architecture, and encourage streamlining processes, just to name a few of the initiatives that affect the way we do business. At the same time, the Office of the Secretary of Defense (OSD) has reduced the level of oversight and review of programs and manufacturers' plants.
>
> While the new acquisition model gives government program managers and their contractors broader control and more options than they have enjoyed in the past, it also exposes them to new risks. OSD recognizes that risk is inherent in any acquisition program and considers it essential that program managers take appropriate steps to manage and control risks...

The level of attention now being given to the subject of risk management stems from the mid 1990s when the DoD established a Risk Management Working Group. This group included in its membership staff from the OSD, representatives from the services, and personnel from other DoD agencies involved in systems acquisition. In July 1996 the working group concluded that Industry has no magic formula for Risk Management, and recommended that the Defense Acquisition Deskbook contain a set of guidelines for sound risk management practices. The working group also recommended that the deskbook contain a set of risk management definitions that are comprehensive and useful to all of those involved. Finally, the working group concluded that the risk management policy contained in DoD 5000.1 series documents was less than comprehensive. This led to the recommendation that DoDD 5000.1 be amended to include a more comprehensive set of risk management policies that focused on:

- the relationship between the Cost as an Independent Variable (CAIV) concept and Risk Management,
- requirements that risk management be proactive (forward looking), and
- establishment of risk management as a primary management technique to be used by Program Managers (PMs).

As a result of the working group's activities the DoD 5000 documents referred to in the 1996 working group report were superseded by a new set of DoD 5000 policy documents issued in late 2000 and early 2001.

Reference 20, based on the material developed by the DoD Risk Management Working Group, is a comprehensive compilation of risk management information and should be considered an essential reference for everyone involved in the acquisition process. Reference 20 is also an excellent information resource that provides definitions for a variety of risk management terms. Definitions of terms like risk, risk event, technical risk, cost risk, schedule risk, risk rating, and others are included. A common thread runs through these definitions that suggest that risk, in an overall sense, should be assessed from two perspectives. First, there is the risk associated with the inability to achieve certain program or process objectives. Second, there is the consequence or impact of failing to achieve one or other or all of those objectives. The mass properties control process is decidedly amenable to this concept. For example, the mass properties control process has very clear objectives that in turn are an essential component of the overall program objectives. In essence the overriding objective of the mass properties control function is to ensure that the mass properties characteristics of the lightship at delivery are such that when the designated loads are applied the resulting loaded ship's naval architectural characteristics fall within contractually acceptable limits. An obvious program objective is to deliver a ship that is contractually acceptable in every respect. Clearly, the consequences of failing to achieve the basic objectives of the mass properties control function is a ship with one or more design deficiencies, each one potentially catastrophic in terms of its impact on the overall program objectives.

The use of acquisition margins in the mass properties control process is discussed in Section 12.5. Section 12.6 discusses management of the mass properties control process. The issue of risk assessment is intrinsic to both of these sections in that acquisition margins are established on the basis of inherent risk and an essential element of the management process is control and oversight of the rate at which the margins are being consumed, which itself is an indicator for residual risk assessment. It can safely be assumed that overall program objectives and mass properties objectives are in jeopardy when the rate at which acquisition margin is being consumed outpaces overall progress.

The iterative nature of the mass properties control process is discussed in Section 12.4 in terms of how initial data is compiled and how that initial data is progressively, over time, refined by substituting increasingly more reliable line-item values for component weight and center of gravity location. The level of confidence that can be placed in the initial mass properties data strongly influences the allocation of acquisition margins. Although initial levels of confidence are likely to be somewhat subjective they should support a reasonable assessment of initial risk. Assuming this to be the case, residual mass properties related risk, as the program progresses from stage to stage can be assessed according to the level of maturity of the current mass properties data. Ideally the maturation process will serve to confirm data values, which would justify a reduction in assessed risk. The possibility exists, however, that the process will reveal a problem area requiring remedial action. Risk management, therefore, must be ready to contend with a variety of possibilities involving various levels of risk as they emerge. Reference 20 provides comprehensive guidance on what is required to accomplish this. Generally speaking, the options available for reducing risk get less and less over time. It follows, therefore, that early identification of potential risk areas is becoming increasingly desirable. A primary objective of risk assessment is to establish as high a level of confidence as possible as early as possible and to retain that confidence level for the duration of the program.

The use of weight and KG reduction initiatives as a means of recovering margin and bolstering confidence is discussed in Section 12.6. Weight and KG reduction initiatives tend to be reactive devices that are used to respond, after the fact, to the emergence of unfavorable weight and moment trends. Often such trends are caused by unexpected weight increases or rearrangements in areas of the ship where design development issues have hampered timely decision-making. As a means of proactively dealing with situations of this type, the aerospace industry and to some extent the offshore industry are applying uncertainty analysis in order to enhance confidence levels relative to achieving program objectives on weight sensitive programs. The Society of Allied Weight Engineers, Recommended Practice No. 11 (21) describes mass properties uncertainty analysis in the following terms:

> Knowledge is required of the accuracies of mass properties data used in space vehicle performance, stability, control, and structural analyses. This is true not only for the total space vehicle but also for elements of the space vehicle such as fluids, deployables, and independently moving parts. Mass properties approaching a limit may require an uncertainty analysis. In some cases, the accuracy of the combination of certain mass properties may be required.

A simple substitution of the words space vehicle with the word ship or submarine and this description becomes applicable to the marine industry. Reference 21 goes on to say, "[M]ass properties uncertainty analyses shall be conducted when mass properties dispersions are required for other analyses, or when the uncertainties may cause mass properties limits to be exceeded." This statement is also readily adaptable to the emerging needs of the shipbuilding industry.

In essence, uncertainty analysis uses a statistical approach to predict the probability that the final weight and center of gravity characteristics of specific weight sensitive items will fall within predefined limits of acceptability. The basic premise being that this type of increased confidence justifies reduced risk. A more detailed discussion ofuncertainty analysis is beyond the scope of this chapter. However, expanded use of the technique can be expected as the requirements for military procurement become more stringent. Additional information on the subject of uncertainty analysis can be found in references 22 and 23.

Generally, the practice of risk management, at least in a formal sense, is not routinely applied to the typical commercial program. However, as worldwide competition for major commercial projects continues to intensify, the use of such devices can be expected to become more commonplace.

12.9 MASS PROPERTIESVALIDATION

Although the ship's predicted mass properties characteristics are closely tracked throughout the design and construction process, actual validation of these predictions and of the system used to make them doesn't happen until just before delivery. The inclining experiment and deadweight survey is conducted close to delivery when the ship is as complete as possible. Comparing the results of this procedure with the values for lightship weight and center of gravity location that are predicted by the mass properties database provides a level of mutual validation for both sources of this information. Generally speaking, good correlation between these two sets of very differently derived data is taken as an indication that the inclining experiment/deadweight survey has produced reliable values for lightship weight and center of gravity location. However, poor correlation presents a peculiar problem that has no immediately obvious solution. Deciding on which of two sets of data, that are supposed to describe the same entity, is correct requires an assessment of the confidence levels that can be placed in each data source. The results of this assessment may require a second inclining, or a detailed review of the weight and moment database.

The previous sections of this chapter have discussed in some length the methods and techniques usually used in order to achieve a reliable mass properties database. Section 12.8 discusses the issue of risk management in terms of enhancing confidence through the identification and reduction of risk.

Reference 24 is one of several documents that provides comprehensive instruction on how to conduct a reliable inclining experiment and lightship survey. Reference 25 addresses the issue of inclining accuracy. Even when reliable methods are used, the accuracy of the end results is influenced by a number of factors. For instance, the ship displacement at the time of the inclining is determined by measuring drafts and freeboards so that the displacement can be read from the ship's hydrostatics data. The accuracy of this one ship characteristic is influenced by a number of inherently imprecise data points. The overall accuracy of the hydrostatic data, how well the ship matches the lines, how accurately the draft marks have been installed and how carefully the drafts and freeboards have been measured all contribute to the overall integrity of just one key characteristic. Inaccuracies can creep in and affect other aspects of the inclining. Inaccurate pendulum lengths and inclining weights and discrepancies with tank soundings can all introduce error significant enough to adversely affect the final results. The deadweight survey itself is one of the more error prone tasks and even unexpected weather changes can be a factor. The list goes on, making it very difficult to define accuracy when applying the term to the inclining experiment and deadweight survey. Nonetheless, if the difference between the predicted values and the inclining results is enough to bring serious doubt into the picture any attempt to assess relative levels of confidence should include consideration of all of these potential discrepancies.

Clearly, poor correlation between the mass properties database predictions and the inclining results could cause major disruptions late in the program. Re-inclining the ship, an expensive and time-consuming proposition, could be the only way to resolve the issue. Resorting to the use of the most conservative values might be an acceptable solution if the discrepancy is not too severe but in the final analysis, the surest way to minimize the risk of anything undesirable happening is to conduct both processes very carefully.

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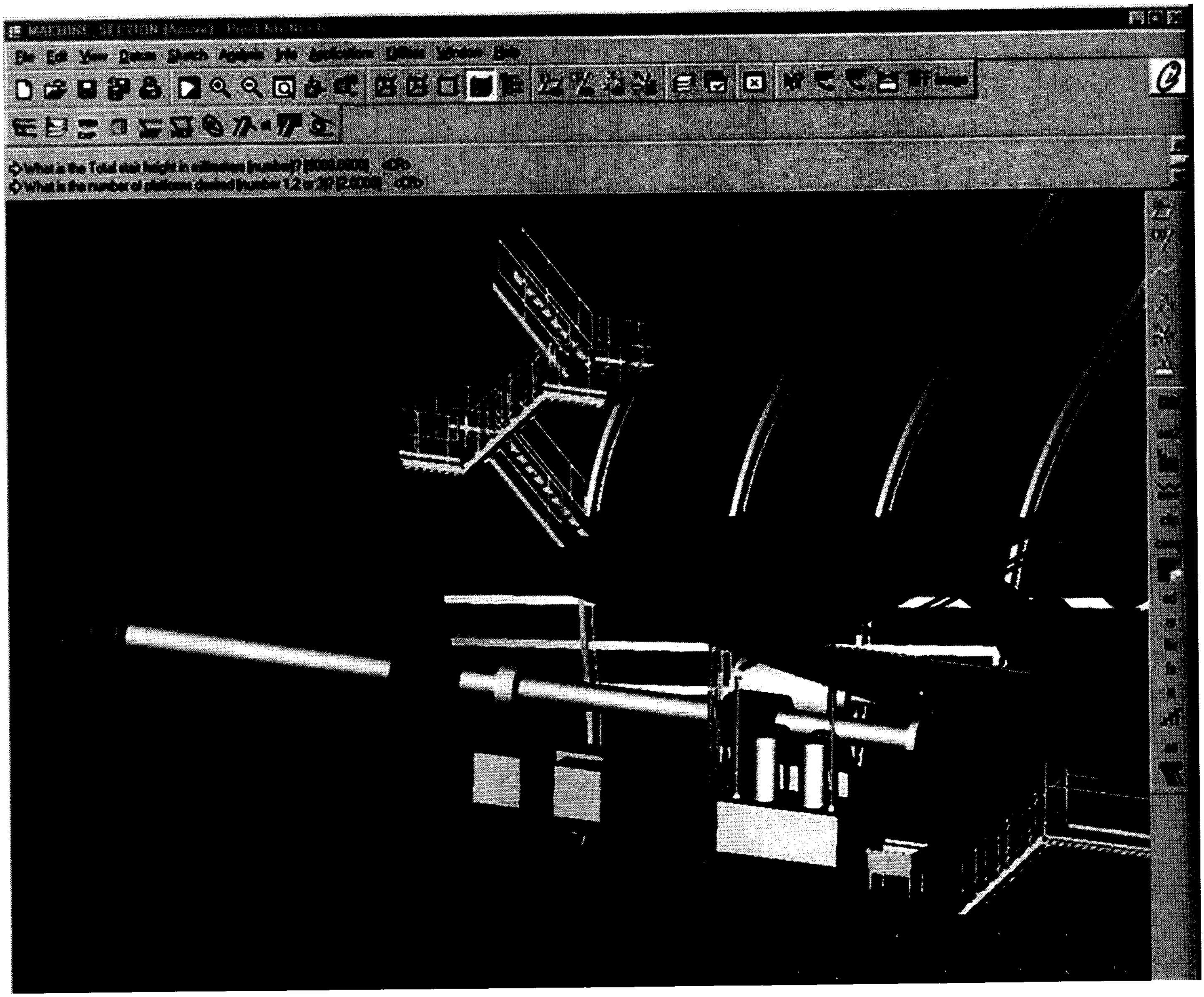


Chapter 13

Computer-Based Tools

Jonathan M. Ross

13.1 NOMENCLATURE

AI	Artificial Intelligence
AP	Application Protocol
CAD	Computer-Aided Design
CAE	Computer-Aided Engineering
CAM	Computer-Aided Manufacturing
CAPP	Computer-Aided Process Planning
CD-ROM	Compact Disk-Read-Only Memory
CFD	Computational Fluid Dynamics
CIM	Computer-Integrated Manufacturing
DAT	Digital Audio Tape
DXF	Data EXchange Format
EDI	Electronic Data Interchange
FEA	Finite Element Analysis
HVAC	Heating, Ventilation and Air Conditioning
IGES	Initial Graphics Exchange Specification
ISO	International Standards Organization
IPPD	Integrated Product and Process Development Model
IPDE	Integrated Product Data Environment
IT	Information Technology
MARITIME	Management and Reuse of Information Over Time
NC	Numerical Control
NEUTRABAS	Neutral Product Definition Database for Large Multifunctional Systems
NIDDESC	Navy Industry Digital Data Exchange Standards Committee
NURBS	Non-uniform Rational B-Splines
OLP	Off-Line Programming
OODB	Object-Oriented Database
OOP	Object-Oriented Programming
PID	Process and Instrument Diagram
PMDB	Product Model Database
SBD	Simulation Based Design
STEP	Standard for the Exchange of Product Model Data

13.2 INTRODUCTION

13.2.1 Background

The shipbuilding industry has used computer-based tools since the early 1950s, initially in accounting, and expanding during the early 1960s to certain design and fabrication activities, then by the early 1970s to the first CAD and CAM turnkey commercial systems (1,2). Perhaps the most striking element in this evolution is the short time span in which it has taken place compared to, for example, the present age of shipbuilding. Table 13.1 illustrates the point. While the birth of industrialized shipbuilding can be set in the middle of the last century, a century and a half ago, the birth of shipbuilding CAD/CAM can be dated from the early 1970s, just over a quarter of a century ago. Significantly, the use of computer-aided tools in shipbuilding is not the sole domain of larger yards but is fast becoming common in mid-size and small yards and in virtually all design firms (3,4).

The table shows the evolution of shipbuilding computer aided tools in general. Not every shipyard evolves through

TABLE 13.I Evolution of Ship Design and Construction Computer-aided Tools (Expanded from (2))

Year	*Hardware*	*Software*	*End Users*
1972–78	Big computing centers, Main frames, Punched cards and alphanumeric terminals	Independent programs, Sequential files, Batch processes	Big shipyards
1979–86	Medium computing centers, Midi/Mini computers, Alphanumeric terminals and graphic terminals	Integrated programs, Medium level independent databases, Interactive processes	Big and mid-size shipyards
1987–94	Local area networks, Workstations, X-terminals, PCs	Fully integrated programs, Single database, Interactive graphic processes, Open systems	Big, mid-size and small shipyards
1995–03	Remote networks, PCs, Workstations, Parallel processors	Windows environment, Object oriented programming, Improved inter-program data exchange	All sizes of shipyards, Design firms

each step of the process. For example, a shipyard may jump from a simple CAD program to a product model program and experience not just an evolutionary step but also a quantum leap in capability (5).

Computer based ship design and construction is an important aspect of making a shipyard more competitive in the world commercial market. Modem computer-aided systems can help address inefficiencies such as the following (6,7):

- Multiple systems used within a single discipline, necessitating the storage of the same data in different places. Integration of work and ensuring consistency are difficult.
- 2D drafting systems, causing difficulties when proceeding to the actual 3D ship design.
- Separate hull and outfit designs, making integration of the final design and inclusion of future changes difficult and open to errors and no integrated planning during deSIgn.
- Aging of the skilled workforce and difficulty in finding young workers willing to work in the traditional dirty, difficult and dangerous shipbuilding environment.
- Inability to meet ever increasing demands by owners for ships of higher quality and shortened delivery times.

A counterpoint to the aging problem is that young workers are more oriented toward the use of computers in their daily work and are often more willing and capable to use CAD/CAM/CIM in ship design and construction than older workers accustomed to little or no use of computers.

Advantages to a shipyard using computers in ship design and construction include the following (10):

- quicker response to requests for quotes and shorter design and construction lead times,
- increased accuracy,
- availability of a reference database,
- availability of a product model to enhance concurrent engineering and production planning activities,
- more flexibility in making design modifications,
- a more controlled environment to help support standardization,
- improved cost control,
- elimination of many tedious manual and repetitive calculations,
- less rework in production,
- less skilled labor needs in production,
- storage of lifecycle data for the ship, and
- configuration arrangement of changes through design and life of the ship.

TABLE 13.II Average Percentage Savings Resulting from Upgrading To 3D Product Modeling for Three Small Shipyards (11)

Element	*Percentage Saving*
Design Labor Hours	30–40
Material Cost	20–25
Production Labor Cost	30–35
Construction Schedule	25–30

As shown in Table 13.1 computer-aided tools may be used to great advantage even in small shipyards if those shipyards follow modem shipbuilding practices, such as the use of block construction instead of *stick building.* A recent poll of three privately owned European shipyards using 3D product modeling for design found dramatic cost savings compared to traditional CAD or manual drafting techniques. Savings are presented in Table 13.n (11).

132.2 Scope of this Chapter

This chapter presents computer-based tools for ship design and production. The following topics are addressed: computer-aided design, computer-aided engineering, computer-aided synthesis modeling, computer-aided manufacturing, computer product models, computer-integrated manufacturing, computer systems integration, computer implementation, and future trends. Also provided are listings of computer systems, projects and initiatives, along with the organizations involved and their nationalities. Computer programs mentioned in this chapter are typically menu driven. Many run real time, although certain functions may be more typically run in batch mode, and virtually all have graphical display capability. In order to improve chapter flow, specific software programs are cited in only one section, though the programs may apply to several sections.

The field of computer based ship design is one of frequent and substantial advances. Thus, while this chapter will provide a general overview, the reader is encouraged to consult professional journals and conference proceedings to gain a current understanding of the technology.

Figure 13.1 Computer-Aided NURBS Hull Design

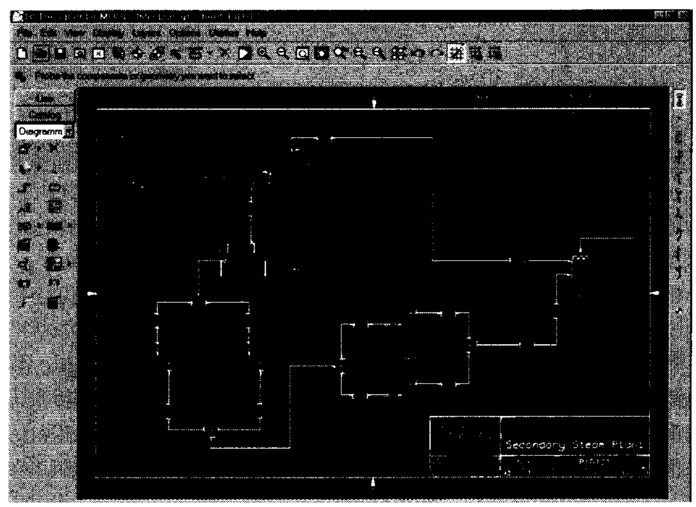


Figure 13.2 Computer-Aided Design of Distributed System

13.3 COMPUTER-AIDED DESIGN

13.3.1 General

Computer-Aided Design (CAD) is a direct outgrowth of the traditional drafting board approach to ship design. CAD depicts geometry and dimensions on a computer monitor and not directly on paper, though an important output of CAD is still paper drawings. Sophisticated CAD systems are much more powerful than computer versions of drafting boards. They may have extensive parts libraries, cut-and-paste capabilities, and efficient, menu-driven user interfaces.

Stand-alone CAD is most appropriate for relatively simple designs such as those developed in the smaller shipyards. For more complex designs, CAE and product model programs are more appropriate.

13.32 Typical Capabilities of CAD Systems

CAD systems have some or all of the following capabilities, running the gamut from 2D line drawings to 3D solid geometry (5,12,13):

Hull design: Hull design may include the development of hull geometry, hull form, and castings. NURBS or B-Spline approaches may be used for fairing. A screen capture of a computer aided hull design of a naval combatant is shown in Figure 13.1.

Decks and bulkheads: Decks and bulkheads are defined as planes within the hull. Included are corrugated bulkheads and deck-to-deck ramps and the inclusion of camber, sheer, knuckles and breaks.

Compartmentation: The hull is divided into separate, identifiable compartments. Compartmentation can be based on spatial analysis.

Profiles and arrangements: Outboard and inboard profiles are developed, as well as arrangements for cargo spaces; machinery spaces; crew, passenger, and associated spaces; tanks; and miscellaneous spaces.

Distributed systems: Design of electrical, piping and HVAC system one-line diagrams is carried out at the diagrammatic level of detail (as shown in Figure 13.2) and at a level of detail sufficient for production and installation.

Drawings: 2D and 3D drawings may be produced in or-

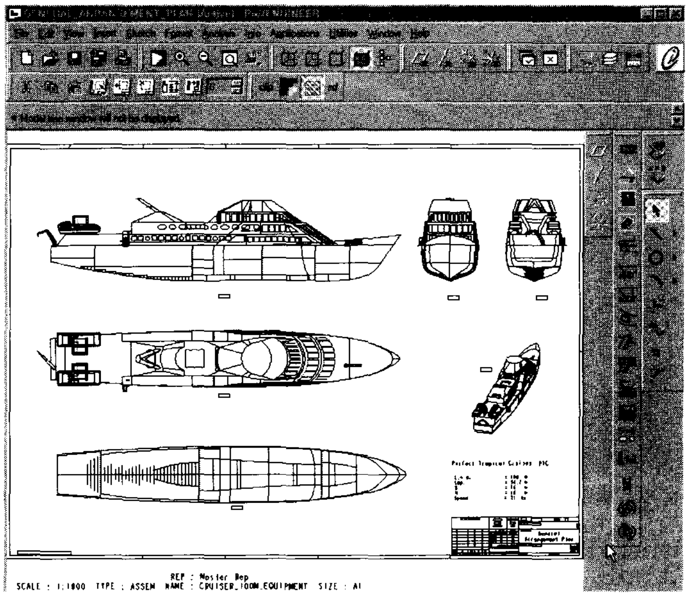


Figure 13.3 CAD Design

thogonal and isometric formats to show hull form, lines, body plan, sections, outboard and inboard profiles, waterlines, schematics and other views of the hull and outfit (Figure 13.3). Included may be dimensioning, text callouts and the generation of tailored title blocks. In addition, drawings may be used to show ship's curves of form and floodable length curves.

Engineering analysis: CAD is commonly used to calculate cross sectional properties such as section modulus and moment of inertia. CAD may also be used to calculate tank areas and volumes, weight distribution diagrams for loading, and hydrostatics and stability data.

Early stage design: Certain CAD systems possess the capability to quickly develop a design to support marketing and proposal efforts. Included are hull, structure, outfit, build strategy and production planning. In addition, CAD may be use to extract profile lengths and plate sizes for early part standardization and material orders.

13.3.3 Examples of CAD Programs

Available CAD programs include the following:

AJISAI CAD-Ishikawajima-Harima Heavy Industries Co., Inc., Japan-for structure (AJISAI-H) and outfitting (AJISAI-F)(12).

AutoCAD-AutoDesk, United States-2D and 3D designing.

Autoship-*Autoship* Systems, Canada-hydrostatics, hull design and fairing, and hull structure (8).

CAD-Link-Albacore Research, Canada-structural modeling within 2D and 3D context (14).

Excel-Microsoft, United States-a general purpose spreadsheet program applicable to many ship design calculations.

FastShip-Proteus Engineering, United States-hull, appendage and superstructure design and hydrostatics.

HICADEC-Hitachi Zosen, Japan, and Odense Steel Shipyard, Denmark-arrangement design, electrical diagrams, hull structure and piping diagrams and layout (12).

HFDS (Hull Form Design System)-United States Navy-hull design and fairing (15).

Maxsurf-Formation Design Systems Pty, Australia-hydrostatics, hull design and fairing, and hull structure (10,16).

NauShip-NAUTICAD sarI, Italy-hull structural design and NC structures cutting tape generation (17).

ProIENGINEER-PTC, United States-2D and 3D designing (18).

ShipGen-Defcar Naval Engineering, Spain (19).

13.4 COMPUTER-AIDED ENGINEERING

13.4.1 General

Computer-Aided Engineering (CAE) automates various ship design calculations in the areas of hull and equipment. While the more typical CAE programs specialize in specific areas, such as ship structure, some are modules of more integrated ship design programs and represent an evolutionary link to product model programs.

13.4.2 Typical Capabilities of CAE Programs

CAE systems have some or all of the following capabilities (5,12,20,24):

Pipe thermal expansion: An analysis is conducted on steam pipe systems to determine thermal expansion and stress. Finite element methods are typically used.

Pipe and pressure vessel pressures: Pipe flow pressure drops, buckling and water hammer forces (on pipe walls, flanges and hangers) are calculated. Compliance with industry standards may be checked.

Hydrostatics and stability: Calculation of hydrostatics for intact and damage stability, and subsequent generation of output such as hydrostatic values, Bonjean curves, deadweight scale, cross curves of stability, freeboard, floodable lengths, curves of section areas and half-breadths.

Volumes and cargo capacity: Calculation and organization by category of the volumes of a ship's compartments, including generation of sounding and ullage tables, volumetric grain heeling moments and tonnage.

Loading conditions: Calculations may be carried out for lightship weight, stillwater equilibrium waterplane, maximum allowable grain heeling moments and weight and center of gravity for modular cargoes (for example, containers and pallet cargoes) and break bulk cargoes.

Speed/power: Using regressions with test series or using Computational Fluid Dynamics (CFD), ship resistance and speed for given power input is calculated.

Plate bending: Calculating forces or line heating requirements for bending curved plate.

Electrical loading: Electric load and fault analyses, as well as cable size calculations.

Weights and centers: Based on the CAD design, weights and centers of gravity may be calculated for the complete ship and for individual elements of structure and outfit.

Structure: Analysis of strength in smooth water and in waves and (for contained liquids) hydrostatic loading; optimization of weight, vertical center of gravity optimization; cost optimization; fatigue analysis; shock analysis; oil-canning calculations; and predictions of natural and forced vibration frequencies. Data may be presented in static and animated multicolor 3D models that show stresses, adequacy parameters and displacements of affected structure. Figure 13.4 shows such a structural model.

Maneuvering and control: Calculations are carried out of rudder geometry and ship maneuverability and control characteristics. Included is consideration of force, moment and motion in the horizontal plane for surface ships and the same considerations in three dimensions for submarines.

Propeller: Propeller selection, geometry and calculation of the propeller characteristics, such as thrust.

HVAC: Flow, heating and cooling calculations are carried out to help size fans, ducting and other HVAC components.

Launching: Calculations for launching over an inclined slipway may include (in a stepwise fashion) ship position, buoyancy, reaction of ground ways and rising and tipping moments. Static and dynamic stability and longitudinal strength may be calculated at the pivoting point and for the ship afloat.

Seakeeping: Ship motions in a seaway are predicted in six degrees of freedom moving forward at a fixed speed. Strip theory is typically used, with roll damping of appendages taken into account. Maneuvering with rudder is calculated. Figure 13.5 shows a visualization of a seakeeping analysis of a ship in oblique seas.

Noise: Airborne and waterborne noise levels are calculated for noise sources located in the ship. Effects of noise treatments such as isolation mounts and enclosures are calculated.

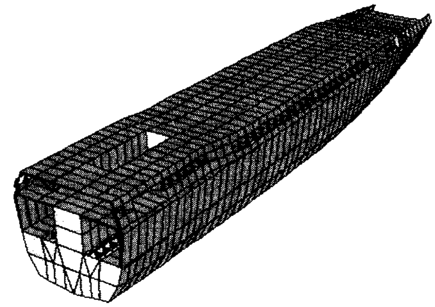


Figure 13.4 Fast Ferry Full Ship FEA Model

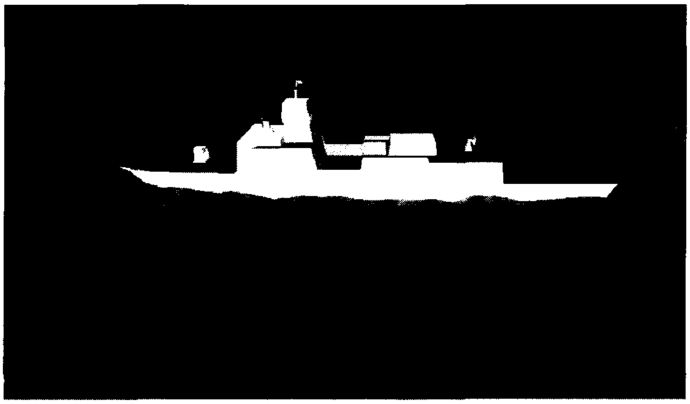


Figure 13.5 Oblique Seas, Seakeeping Visualization

In a class by itself are computer programs for the initial design and cost estimation. These programs are usually parametric, and produce their technical and cost estimates based on historical data. Some are quite sophisticated, with many input parameters. Their accuracy depends upon the validity of the parametric relationships, and they are useful only within their range of historical data. These programs are used to produce initial designs for trade-off analysis, and for quick initial response to shipowner inquiries.

13.4.3 Examples of CAE Programs

Presently operating CAE programs include the following:

BAS CON-Korea Research Institute of Ships and Ocean Engineering, Korea-integrated system to develop ship concept designs (25).

NavCad-Hydrocomp, Inc., United States-for resistance and power predictions and optimum propeller determinations.

GHS-Creative Systems, Inc., United States-for determination of ship hydrostatics, stability and longitudinal strength.

HICADEC-P-Hitachi Zosen, Japan, and Odense Steel Shipyard, Denmark-used for pipe systems calculations, such as pressure drop (12).

HFDS (Hull Form Design System)-United States Navy-develops predictions for powering, seakeeping, maneuvering and stack design through series data, parametrics and computational fluid dynamics (15).

MARINE (Mitsubishi Advanced Real-time INitial design and Engineering system)-Mitsubishi Heavy Industries, Japan-Carries out initial design, naval architecture and ship performance calculations to support rapid response of marketing and proposal efforts (12, 26).

MAESTRO-Optimal Structural Design, United States-structural design, analysis and optimization program tailored to stiffened thin skin structures of ships.

NASTRAN-National Air and Space Administration (Original Version), United States-general purpose FEA program that may be used for ship structural analysis (12).

POSEIDON-Germanischer Lloyd, Germany-software to develop structural design from a rules-based or rational (PEA) approach to aid in the classification process (27).

SafeHull-American Bureau of Shipping, United States-rationally-based PEA program to verify yielding, buckling and fatigue strength of ship structures (28, 29).

ShipWeight-BAS Engineering, Norway-estimates and follows up (during construction or design changes) weight and center of gravity of a vessel (30). A screen capture of this program is shown as Figure 13.6.

Weightprog-Germanischer Lloyd, Germany-estimates steel and light-ship weights (31).

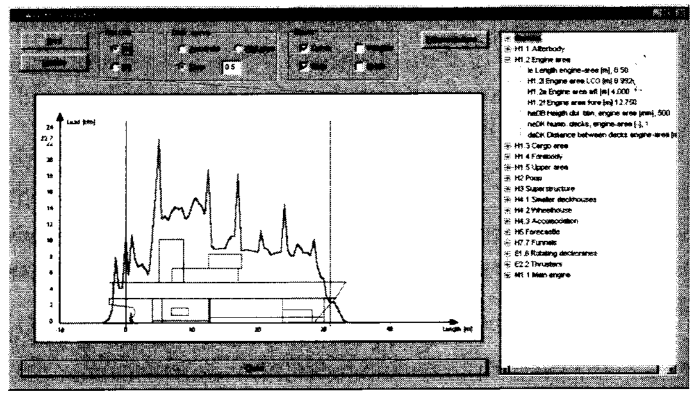
Examples of initial design programs include the following:

Vision (Virtual Integrated System for Shipbuilding Innovation)-Was developed by NAMURA Shipbuilding of Japan to respond quickly to inquiries from shipowners (32).

13.5 COMPUTER-AIDED SYNTHESIS MODELING

13.5.1 General

Computer-aided synthesis modeling uses trends from existing design data to approximate a design of a new vessel or a modification to an existing vessel. This approach is quick and inexpensive, and supports marketing, budgetary cost estimation, and initial production planning. Synthesis modeling also provides a design baseline for preliminary design.



13.6 Ship Weight Distribution Visualization

13.5.2 Typical Capabilities of Computer-Aided Synthesis Modeling

Computer-aided synthesis models range from the simple to the complex. Models have been developed to address a wide range of naval and commercial ships and vessels, and a number of models include iterative capabilities to optimize results. Some synthesis models are initialized with a parent hull, while others consider trends of a number of hulls of similar ship types. The models may address design, operation, and cost issues, as described below (33, 35):

Ship design: Ship design elements may include hull geometry, hull subdivision, aviation support, deckhouse, hull structure, appendages, resistance, powering, machinery, auxiliary systems, and weight (33).

Ship operation: The following elements may be addressed: cargo deadweight, cargo tank and hold capacities, service speed, and voyage length and duration (33).

Cost information: Cost may be estimated for ship materials, shipyard production, and ship operation (33).

13.5.3 Example Computer-Aided Synthesis Modeling Programs

ASSET (Advanced Surface Ship Evaluation Tool)-United States Naval Surface Warfare Center, Carderock Division-used in the exploratory and feasibility design phases of naval surface ships (33).

PASS (Parametric Analysis of Ship Systems)-Band Lavis Associates, United States-used to support ship and vessel synthesis designs (34).

GCRMTC Ship Synthesis Model-Gulf Coast Regional Maritime Technology Center/M. Rosenblatt & Sons-iterates parent hull forms to generate design and cost estimates (35).

Commercial Ship Design Synthesis Model-University of Michigan, United States-used for ship design and operating economics (36).

13.6 COMPUTER-AIDED MANUFACTURING

13.6.1 General

Computer-Aided Manufacturing (CAM) programs help bridge the gap between ship design and construction. CAM programs develop data for use in areas such as welding, cutring, lifting, bending, forming, planning, and monitoring.

116.2 Typical Capabilities of CAM Systems

CAM systems have some or all of the following capabilities (6,7,12,23,37-41):

Accounting for weld shrinkage: Automatic calculations are made (and avoidance instructions may be developed) for angular distortion and buckling of plates (especially thin plates, 10 mm) caused by gas cutting and by welding stiffeners and other structure to a plate. Traditionally, calculations have been empirical, based on experiments; more recently, numerical techniques have been introduced. Weld shrinkage is characterized as in-plane di9tortion, and is a critical element in a shipyard attaining the capability for neat cut fabrication techniques. Out-of-plane distortion may occur as well as in-plane distortion. Out-of-plane distortion is commonly corrected by flame straightening and mechanical rework. The out-of-plane distortion as well as the corrective measures may exacerbate the in-plane distortion and contribute to weld shrinkage of a plate (1).

Dimensional control: Important dimensions for hull and outfit interfaces are monitored with technologies such as infrared and photogrammetry.

Interface between product model and robots: Data involving geometry, welding, cutting, assembly, testing and painting are transmitted from the product model to open architecture controllers that develop robot path programs. Commonly, robot functions are simulated in a computer for refinement prior to actual production.

Robotic programming: Programming may be off-line programming (aLP) and may be agent based. The programming is designed so that the robot avoids collisions, gains access to weld locations and optimizes tool (for example, welding torch) orientation. For repeated details, such as collars, a macro may be developed; each time the detail is called for, the macro is used. Needs for automatic robotic programming include geometric information (definition of ship structural surfaces and interfaces), welding data (weld size, filler metal type, direction and order of welding), and robot motion planning data (torch orientation and adaptation techniques to avoid interferences and manufacturing inaccuracies).

Production management support: Cutting, welding, material control, fabrication and erection processes may be simulated, tracked, documented and monitored on interactive screen displays and in batch print-outs. Included may be what-if studies of part or all of the ship construction process. Also, data on production, cost and quality assurance may be collected and statistically analyzed. Data may be exchanged with planning and technical programs to improve production processes.

Lifting planning: Calculates lifting and rigging requirements for structural assemblies so that the assemblies may be properly sized to be within the capabilities of a shipyard's cranes and other lifting devices.

Paint design and monitoring: Planning for automated painting, including coating definition by surface to be painted and prediction of coverage over the item to be painted.

Part coding and Hierarchy: Assigns numbers to piece parts, and often links parts, subassemblies, assemblies, etc., in a hierarchical fashion.

Nesting: Arrangement on gross plates for cutting of plate shapes may be made, along with the definition of NC cutting paths. Similar capabilities may be present for arranging and cutting profiles and pipe.

Plate and profile forming: Data may be generated to form curved plate. The data gives the pin heights of the jig bed, together with a graphic illustration of the plate position and reference dimensions for checking purposes. In a like manner, data may be generated for bending templates for plates and profiles.

Pipe bending: Data may be generated to bend pipes, allow for spring-back, and define positioning of hangers and end fittings. The data may be NC, to feed directly to automatic bending machines, or in the form of isometrics and sketches that include material, dimensional and tolerance information.

Cable lengths: Data may be generated to define cable lengths and cable installation work orders.

13.6.3 Examples of CAM Programs

Presently operating CAM programs include the following:

AMROSE (Autonomous Multiple Robot Operation in Structured Environments)-Odense University and Odense Steel Shipyard Ltd., Denmark--off-line programming system for welding robots (41).

CIPS 200O-Norddeutsche Informations-Systeme GmbH, Germany-rule-based system for manufacturing of piping systems (12).

DINCOS-Norddeutsche Informations-Systeme GmbH, Germany-links product design, production and production planning (42).

HICADEC-H-Hitachi Zosen, Japan, and Odense Steel Shipyard, Denmark. nesting, as well as parts naming (12).

LASC-Hitachi Zosen, Japan-provides an analysis of the paint spray created by nozzles placed in 3D space. May also be used to check the effectiveness of tank cleaning arrangements (12).

Lead Control-Norddeutsche Informations-Systeme GmbH, Germany-a shop floor system for controlling production equipment, such as robots, transportation systems and NC machines (12).

LIPSS-Hitachi Zosen, Japan-simulates the lifting of assemblies and arrangement oflifting pads, considering standard crane rigging components, such as spreader beams and variable length cables. Blocks' weights and centers are calculated (12,43).

MONMOS-Odense Steel Shipyard, Denmark--carries out dimensional control using infrared technology (12).

NC-Pyros Pro-Albacore Research, Canada-converts CAD drawings to NC code for 2D burning tables (13).

PROHITS (Production-Oriented Hull Information Technology System)-Daewoo Shipyard, Korea-supports parts hierarchy, material control, bills of material, nesting and quality control (44).

PMS (Product Management System)-Mitsubishi Heavy Industries, Japan-U sed for planning, scheduling and tracking subassembly and block progress and labor loading in the shops with plan views and Gantt charts (12).

ROB-IN-Odense Steel Shipyard, Denmark-uses data from product model to generate NC instructions for robots (for example, for flat panel welding robots)(12).

RoboPlan-Norddeutsche Informations-Systeme GmbH, Germany-off-line programming system for welding robots (12,40,45).

ShipCAM-Albacore Research, Canada-pin jigs, inverse bending curves, and shell plate development (13).

TOPOS-Hitachi Zosen, Japan-provides for viewing of an assembly to be coated with paint and the definition of the paint coating for each surface (12).

13.7 PRODUCT MODEL PROGRAMS

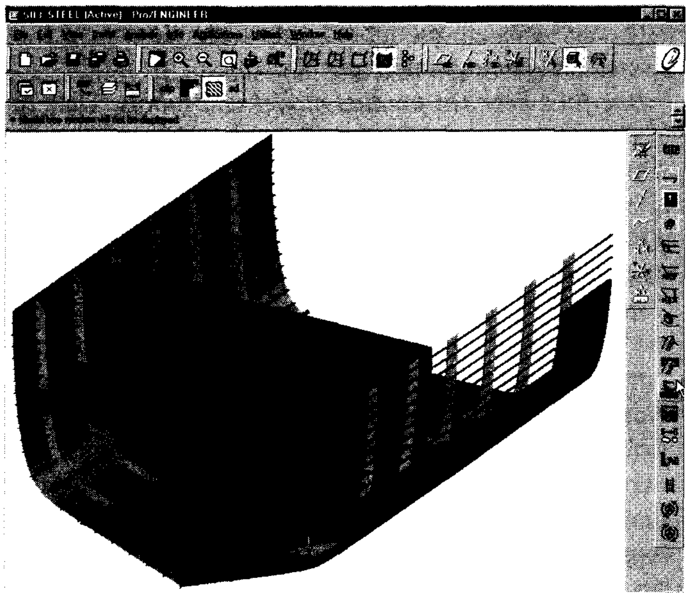
13.7.1 General \.

A product model program supports the analysis and informational needs for the engineering, design, construction and maintenance of a ship. The product model database contains geometric information such as hull form definition, and non-geometric information such as equipment weights. The information is contained in a central database and is available as graphical displays, hardcopy printouts, and as electronic files for use by NC production equipment. The database provides a single source for complete, updated and consistent information to all involved in the design and production processes (46,47).

Early versions of this concept were usually tailored to a specific project and were not broadly enough based to address the general integration of design data and process information that together define a ship. More modem versions of the concept are tailored to ship design and construction, yet are general enough to be used for different ship projects (48).

An important aspect of product model programs, is their three dimensionality, as shown in Figure 13.7. Traditional ship design is carried out in 2D in the preliminary stages and extended to 3D in the detailed stages. The extension from 2D to 3D results in a large expenditure in time and labor (49). Product models enable the designer to either begin in 3D or to easily progress from 2D to 3D, realizing savings over the traditional approach.

Product model programs make possible an integrated



13.7 Steelwork Graphical Display from a Product Model Program approach to ship design and construction within a multi-user environment. This integration is that existing *within* the product model program (not the integration among different product model programs, which is discussed elsewhere in this chapter) and implies elements such as the following (5,50):

- the designer works in a fully interactive 3D graphic environment,
- information about hull form, decks and bulkheads is always available to all designers using the product model,
- a designer working in a zone or block of the ship has available the information of other zones or blocks (contiguous or not),
- outfitting designers in a zone use the last updated information of the hull structure, available in the product model database, and
- automatic references to the hull, decks, bulkheads, and frame system or to any ship part can be obtained when generating drawings for production (for example, plan drawings, pipe isometrics and perspective drawings).

The product model approach enables designers to use the same model of a ship, from the earliest stages of design all the way to production, helping to maximize consistency of data throughout the design process. Advantages of product models include: decreased design hours, reduced lead time, increased productivity, early detection of interferences, ease in making changes, a drastic reduction of information errors, a primary source of design information, and the availability of production-oriented data. This technology may include expert systems and artificial intelligence (48,51,52).

13.7.2 Typical Capabilities of Product Model Programs

Product model programs have some or all of the following capabilities (5,12,18,53-56):

Single integrated database: The product model database is common to all modules that make up the program and is thus shared by all modules; there is no need for data conversion between modules. Each piece of data is represented in one place in the database. Other features of a single database may include:

- simultaneous access of users and control of access authorization,
- integration of hull and outfit,
- automatic maintenance of information consistency and cross references,
- control of information integrity, and
- integrated design and production planning.

Graphical user interface with consistent format: Included may be features such as:

- multi-window graphic system with user-controlled zoom functions for each window,
- ability to reproduce previous session activities and commands through journal files, and
- look and functionality of the graphical user interface is consistent among all modules of a program.

Topological (associative) relationships among components: Logical connections are present among related elements in the hull. With topology, a change to one element (for example, ship beam) automatically generates changes to related elements (for example, width of decks). This approach increases the ease by which designers can make changes to a design. In the area of outfitting, the change of a pipeline diameter will result in proportional updates to all individual pipe segments, flanges, valves and other components in the pipeline, all through a single command. By using approaches such as topology and parametrics instead of pure geometry representation, the ship may be modeled in a very compact form, saving database storage space. Topological modeling may be used in hull structure definitions to facilitate design alterations and new product development based on derivatives from previous designs.

Macros: Small software routines may be provided to carry out common, repetitive tasks in the design process.

Parametric definitions: Cutouts, brackets, lightening holes and the like are defined by means of set dimensions and angles (for example, a V-shaped cutout may be defined by the radius of the curved section and the height of the straight section; thus, the cutout is completely specified by two numbers).

Open data structure: An open data structure allows for data retrieval to support add-on programs, such as numerically controlled cutting and bending; purchasing; material handling and tracking; robotic interfacing; development of build strategy; and project management.

Generation of structural penetrations: Piping and stiffener penetrations through structural plate and profiles are automatically generated based on standards resident in a library (see also, *Libraries* below).

Visualization of geometric model: The ship hull and outfit geometry may be viewed in 3D, with the capability for the viewer to rotate, scale, change shading, zoom, and change viewer position.

Build strategy: Assembly information is assigned in a hierarchical fashion to parts, subassemblies, assemblies and blocks (and other intermediate structures) to enable visualization and construction sequence planning.

Generation of drawings: Based on the product model database, drawings are generated and printed on various sizes of paper for structure and outfit in the form of 2D, 3D and isometric drawings. Drawings may show the complete ship or separate elements, such as structural assemblies and pipe spools. Included is the ability for the user to tailor formats to include information such as stiffener end cuts, drain holes, pipe bending information and orientation of welded flanges on pipes (following the bending operation).

Nesting: Plate, profiles and pipe may be nested, and NC cutting instructions may be generated for transmission to NC cutting equipment.

Bill of materials: Bills of materials are automatically generated for structure and outfit as the design progresses.

Walkthrough: A simulated 3D walkthrough may be carried out, in which the viewer moves through the product model to, for example, check interior spaces such as passageways and engine rooms to ensure sufficient maintenance clearance is available (Figure 13.8). This is a graphics-intensive capability.

Part data: Each part may have associated with it data such as weight, material type and quality, marking lengths, ship construction block number, shaping flags, cutting lengths and parameters for profile end cuts and geometry. This capability is also known as attribute information.

Libraries: Located in the database may be libraries of structural plates and shapes; weld types; parts (standard and parametric); and outfitting components, all with attributes such as material type and dimensions, including space for operation/maintenance/repair in place. Outfitting components may include additional attributes such as power ratings for motors and flow ratings for pumps.

Structural shape and piping attributes may include definitions of bending contours and of end treatments, such as:

Hull/outfit integration: Integration is present between the **hull** and outfit portions of the product model as shown in Figure 13.9.

lnteiference checking: Interferences of structure and outfitting elements are checked; either real time or batch, and descriptive warnings are provided to the user. This capability may also be used to notify the user of manufacturing shortcomings of the design. For example, in the design of a piping spool, a warning may inform the user that there is insufficient straight length of pipe at each side of a bend to permit clamping the pipe in the bending machine.

CAD/CAM Capabilities: Product models commonly include the types of capabilities found in CAD and (to a more limited extent) CAM programs, such as developing structural and outfitting arrangements, designing distributed systems, carrying out naval architectural calculations, and providing input to drive NC cutting machines.

Multi-User Capabilities: Product model programs may support design-build teams whose members are located at different geographical sites.

Features may include:

- ability to carry out concurrent development of designs, and
- conferencing, with communication through text, audio and video.

Production support: Standard methods may be generated for cutting, bending and fabricating profile and plate parts, tailored to the shipyard's capabilities. The resulting data, for individual piece parts and assemblies, may be transmitted to automated and robotic production equipment such as cutters, welders and benders.

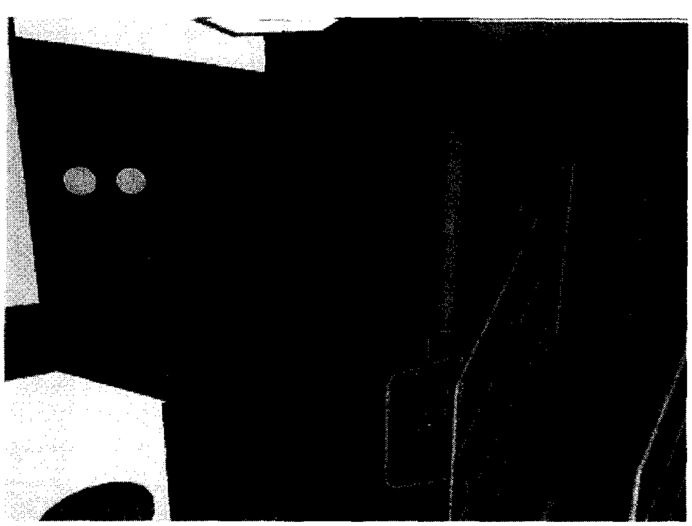


Figure 13.8 Simulated Walkthrough in a Ship's Generator Room

Figure 13.9 Example of Integrated 3D Model of Hull and Outfit

13.7.3 Examples of Product Model Programs

Presently operating and under-development product model programs include the following:

CATIA/CADAM-Dassault Systemes (developer-France), IBM (distributor-United States) (54).

CSDP (Computerized Ship Design and Production System)-Korean Research Institute of Ships and Ocean Engineering, Korea (56).

EPD (Electronic Product Definition) Computervision Corporation, United States (12,53).

FORAN-SENER Ingenieria y Sistemas, S.A., Spain

GODDESS (GOvernment Defence DEsign of Ships and Submarines)-Ministry of Defence, United Kingdom (58)

mCADEC-Hitachi Zosen Corporation (Japan) and Odense Steel Shipyard (Denmark) (12).

GSCAD (Global Shipbuilding Computer Aided Design)-Intergraph Corporation and the Global Research and Development Company, Inc. (GRAD) international consortium (59).

MATES (Mitsubishi Advanced Total Engineering system of Ships)-Mitsubishi Heavy Industries, Japan (26).

NAPA (the Naval Architectural Package)-Napa Oy, Ltd., Finland (51)

NUPAS-CADMATIC-Numeriek Centrum Groningen B.Y., (Netherlands) and Cadmatic Oy (Finland) (3,60,61).

pm (Product Model by Hitachi Zosen)-Hitachi Zosen Ariake Works, Japan (62).

PROMOS (PROduct Model of Odense Shipyard-Odense Steel Shipyard Ltd., Denmark (63).

ProIENGINEER Shipbuilding Solutions-PTC, United States.

TRIBON MI-Tribon Solutions, Sweden (64).

These programs are representative of today's state-of-the art in the product model approach. The programs, or at least the modules which comprise the programs, have been developed over a period of years and are still being improved (48).

13.8 COMPUTER-INTEGRATED MANUFACTURING

13.8.1 General

Computer-Integrated Manufacturing (CIM), is an integration of all data processing that supports ship design and construction, including design, engineering, testing, production planning and production control, all using a common database. The most advanced shipyards today operate in an interfaced, but not totally integrated, CIM environment. A major objective of CIM is to minimize redundant operations within and between computer programs, particularly with regard to manual data input (7,46,65,66).

Particular goals of CIM include the following (67):

- flexibility to support multiple product lines (for example, tankers as well as containerships),
- support of small-lot as well as series production runs,
- reduction of production lead-time,
- fast processing of information to help enhance design, production and administration efficiency,
- minimization of inventory levels, and
- quality improvement, leading to techniques such as neat fit-up of assemblies and blocks.

During the introduction of CIM within a shipyard, it is recommended that the yard focuses on one or two of the goals, and then expands in steps to the others.

Although the concept of CIM has been around for some time, its successful implementation in shipyards only recently has become practical, based on computer capabilities. Problems associated with successful implementation ofCIM in a shipyard may include the following (67,68):

Conflicting definition of CIM: Different parts of the organization may view CIM in different ways, resulting in a lack of coordination and misunderstandings.

Indiscriminate copying of other CIM systems: The selected CIM system may work well for another shipyard or within another industry, but important technical and cultural elements particular to the implementing shipyard are not considered.

Misunderstanding the CIM system: For example, the selected CIM hardware and software may be inadequate or inappropriate to the particular shipyard environment. Also, shipyards may not set progressive goals, but attempt to attain all possible CIM benefits simultaneously. Careful planning and balance are parts of a successful implementation of CIM.

Omitting consideration of human factors: The mix of worker skills is different in a CIM environment than in a traditional shipyard environment. Workers in a CIM shipyard are not cogs performing well-defined, unchanging, repetitive tasks but rather must be flexible in their approach to shipbuilding and must possess advanced skills in problem solving and interactions with other workers.

Omitting consideration of shipyard organization: Another way to state this problem is *too much attention placed* *on the CIM hardware and software and not enough on the organization.* Shipyards often do not consider changing their management-worker organization. The traditional steep hierarchical organization is often ineffective in the environment of advanced manufacturing processes, where rapid change is the norm. Better suited are flatter organizations in which members adaptively form virtual teams to address problems as they arise.

Omitting process improvements: Shipyards may not understand that the successful adaptation of CIM must include an improvement of shipbuilding processes. All design and production processes should be reviewed, then changed, deleted or added to in order to best function within the CIM system.

13.8.2 Typical Capabilities of CIM Systems

CIM systems have some or all ofthe following capabilities (7,12,66):

Integration: The hallmark of CIM is a high level of communication and information management within and between technical and administrative programs and maintaining the information on a common database.

Management: Management is enhanced through increased capabilities in communication, tracking and reporting, within the shipyard and with customers, regulatory bodies and vendors.

Material Control: This applies to hull and outfit, at all stages of design and production, and may include procurement and inventory control and marking (for example, bar codes) (23).

Scheduling: Schedules may be developed and modeled for overall ship construction purposes, management tracking and shop floor use. Graphical presentation is typical. By using the CIM context, scheduling may be made more efficient than when it is carried out as a separate function. For example (69):

- information necessary for design and process planning is likely to be acquired at an earlier stage of design as compared with a non-CIM system. Thus, the size of the workload can be grasped earlier,
- possible differences among the scheduling for different terms, such as that between the long and medium terms, can be more easily adjusted, and
- scheduling can be more accurately carried out in a Deming *plan-do-check* cycle in controlling the performance of work.

Production Planning: Included is consideration of time, resources, cost estimation, shop areas, and tracking by trade. Presentations may be graphical, especially for activity planning and detailed resource and workshop planning. Expert processes may be introduced, which can (70):

- reduce the skill level demanded of a planner,
- reduce planning time, and
- simulate the production sequence.

In this case, knowledge needed to carry out production planning manually, such as production rules, would be contained in the expert process program:

Production Automation: Automation through production-oriented data that is used in automated process equipment, including robots for processes such as cutting, welding and painting.

Purchasing: Regarding vendors, ship material and equipment specifications and purchase orders may be directly transmitted between yard and vendor. In addition, initiatives are being carried out with an aim to improve shipyard/vendor communications (see below) and to establish strategic relationships. Such supply chain integration has been extremely successful in the automotive industry and steps are being taken in this direction by the United States aircraft industry. Potential payoffs include cost reduction and shorter cycle times (71,72).

Data States: Data states may be associated with each part or component in a ship during the course of a project. During design, the data state may move from conceived, to decided (by designer) to broadcast (for review), to approved (by project management). Once approved, the data state may be on hold, or it may progress to planned (purchase and installation), to implemented (installed), to tested, and finally, to as-built.

13.8.3 Examples of CIM Programs

Typically, CIM programs comprise interfaced combinations of stand-alone programs. Examples of such programs include interfaced combinations of programs described in preceding sections as well as the following:

MHl's CIM-Mitsubishi Heavy Industries, Ltd., Japan-an interfaced combination of MARINE, selected CAE systems, MATES, Factory AutomationIRobotics systems, DAVID, and Production Management System (26).

SUMlRE-Sumitomo Heavy Industries, Ltd., Japan-an interfaced combination of conventional CAE systems, SUMlRE-VPS, Basic Design System, Steel Material Procurement System, SUMlRE-H, CAM systems, SUMIRE-F, Production Planning System, and Fittings and Equipment Procurement System (73).

MACISS (Mitsui Advanced Computer Integrated Shipbuilding System)-Mitsui Engineering and Shipbuilding

Co., Ltd., Japan-addresses hull design, outfitting design, assembly procedures, scheduling of jobs, process control and distribution control of parts and components (74).

IHI's CIM-Ishikawajima-Harima Heavy Industries Co., Ltd., Japan--composed of four major subsystems: AJISAI (Advanced Jointless Information System by Assimilation **and** Inheritance), PE (Production Engineering), KLEAN (Kure LEAN production scheduling) and the FA (produc**tion** data information system for Factory Automation) (75).

An ambitious example of a CIM system is the effort begun in fiscal 1989 and carried out by seven Japanese shipbuilders through the Shipbuilders Association of Japan, the Shipbuilding Research Association of Japan and the Ship and Ocean Foundation. This project is aimed at developing a General Product Model Environment (GPME) and then advanced CIM. The GPME system specification (called a frame model) covers 15 application systems (5,12,65,76):

1. *fabrication production management:* Uses rule-based techniques and historical production data to develop construction, erection and fabrication schedules.
2. *design management:* Develops and tracks the design development schedule, ensuring that designs are produced in a timely manner in order to support production.
3. *project information:* Development of plans and arrangements drawings. An automated approach is used so that changes may be incorporated easily.
4. *resistance and powering:* Resistance and powering calculations based on initial hull values with updated calculations to reflect design changes.
5. *hull structural design:* Structural calculations of the hull, including the midship structural materials and structural parts.
6. *outfitting equipment listing:* All ship's outfit from the contract specification.
7. *outfitting Equipment Arrangement:* The arrangement of all ship's outfit, including working spaces, engine room and accommodations. Develops equipment bill of materials for use by purchasing. At the system level, a rule-driven feature assists the design process.
8. *distributed systems design:* Distributed systems (for example, duct, cabling and piping) design, based on machinery arrangement and hull size. Assembly information is produced for piping and ducting.
9. *painting design:* Structure and outfit painting design (dry film thickness, number of layers and paint name).
10. *steel plate processing:* Definition of type and quantity of steel plate, and development of NC and robot information for cutting and shaping.
11. *build strategy:* Development of section, unit and block divisions; set-up of sequence of operations for fabrication and erection; development of detailed piece part and subassembly diagrams; production of preliminary build schedule.
12. *quality program:* Development of quality specifications in the form of a manual and recording of accuracy information during construction.
13. *high-level scheduling:* Development of a milestone schedule to support the contract delivery date of the ship within the constraints of the shipyard facility (manufacturing resources).
14. *short-term scheduling:* For time spans between one day and one week, at the level of individual persons and individual NC machines. Feedback is provided, based on actual production progress, and this is fed to the high-level schedule.
15. *material control and tracking:* Defines material needs and provides reports, and tracks material from arrival at the warehouse to process and assembly areas.

The GPME is viewed by its developers, not simply as a computerized way to carry out business using today's processes, but rather the introduction of fundamentally new processes. This in turn reflects on the GPME program requirements, which must be tailored with the new processes in mind. This is of course an interactive effort of refining the program and the processes, which those programs support.

13.9 COMPUTER SYSTEMS INTEGRATION

13.9.1 General

While CIM addresses integration from the perspective of the individual shipyard, integration is also of great value between different organizations and between different computer systems. For example, design and production efficiency will be enhanced if there is a high degree of integration among members of organizations that join together to carry out a large or complex project. Members may include shipyards, suppliers, classification societies and owners. This inter-organizational integration is made immeasurably easier if there are interfaces among the computer systems of the various member organizations.

There are different levels of integration:

Manual integration: The results of one program (for example, CAD drawings) must be keypunched to another program (for example, bill of materials). In reality, this is "no integration."

Module Integration: Various modules of a program share data with one another. For example, hull form data is communicated to the module that calculates ship stability. User interfaces may differ from module to module, and commonly this type of integration cannot support combining results from among the various modules to make a unified presentation. A program with this level of integration is sometimes characterized as an *inteifaced* system rather than an *integrated* system. Typically, each module has its own database,

Product model integration: A more advanced level of integration is by means of a product model, a detailed, 3D description of the ship and its major systems. The product model has a common database that is shared by all the modules; that is, there is no need for data conversion among the modules.

Enterprise integration: More advanced yet is integration of not only the design, engineering and construction aspects encompassed within the product model program, but programs addressing shipyard management and third parties. Enterprise integration may focus on a single shipyard (as with CIM) or may extend to several shipyards and their associated vendors, customers and regulatory organizations.

In the end, integration necessitates linking multiple databases. This is frequently quite challenging. At least eight semantic inconsistencies may arise between data in multiple databa ses (77),

1. name conflicts,
2. data type/representation conflicts,
3. primary/alternate key conflicts,
4. referential integrity behavior conflicts,
5. missing data and null values,
6. level of abstraction,
7. identification of related concepts, and
8. scaling conflicts.

Further discussion is presented in the following sections regarding computer integration in the shipbuilding industry and progress to date.

13.9.2 Interfaces Among Programs

The need to communicate among programs is a traditional need of users. However, even though the international community has been devoting efforts to develop standards for communication, achievements to date have generally been limited to the exchange of 2D and 3D graphical data with associated text, characteristic of CAD drawings. For example, geometric and graphics data is commonly transferred in IGES or DAT standards (78,79).

A number of proprietary (non-standard) interfaces have been developed, both one- and two-way, between programs, including product models. These are limited in nature, meant for the specific programs and not intended as general standards for data exchange.

There is also a need for a neutral robot programming language. Presently, each robot vendor has it's own language. Progress in this area appears less active than in the CAD/CAM area (7).

The development of interfaces among computer programs must, in the long run, be based on standards. Developing standards in an internationally competitive industry such as shipbuilding is a sometimes-controversial process. There are numerous advantages to using standards for data exchange, including increased speed, fewer errors, and a resultant reduction in design labor and procurement costs. Also, standards enable the user to select *best in class* software for each step in the design process. Disadvantages include a potential for widespread problems if there are defects in the standards, restricting software innovation that extends beyond the scope of the standards, and limiting the user to the lowest common denominator features among the programs being linked (8).

The present trend in the shipbuilding industry is toward further international standardization, mainly because of the international nature of the industry. This trend is not only evident in the highly industrialized shipbuilding nations, but also in the emerging Chinese yards, where international standards are credited as a very important factor in successful international market penetration and as a vehicle for increasing yard efficiency (9).

13.9.3 Examples of Computer Systems Integration Initiatives

Examples of computer systems integration initiatives include the following:

CALS Technological Research Association-Seven Japanese shipyards, the classification society NK, and the ship owner NYK-A massive initiative aimed at setting up an electronic web, using the Internet, for exchanging shipbuilding data, especially relating to product models (52).

NIDDESC (Navy Industry Digital Data Exchange Standards Committee)-A United States Navy and United States marine industry working group, NIDDESC has been working on product model standards since 1986. It has developed proposed standards for ship structure, ship piping, ship ventilation, ship cabling and wireways, and ship outfitting and furnishings. NIDDESC is the UNITED STATES coordinating body for STEP (80).

STEP (Standard For the Exchange of Product Model Data (STEP ISO 10303)-This is an application-specific neutral file for representing and exchanging product model data. STEP is being developed under the auspices of ISO (International Standards Organization). The goal of STEP is to develop standards, called application protocols (APs). In 1993, a cooperative effort between NIDDESC (for the United States) and NEUTRABAS and MARITIME (for Europe) was initiated. The effort resulted in approval by ISO to develop five application protocols for ship product model data exchange. These five are:

AP 215 - Ship Arrangements,
AP 216 - Ship Molded Forms,
AP 218 - Ship Structure, and
AP 227 - Plant Spatial Configuration (Piping, HVAC, and Cableways).

Possible future APs will address mission systems, outfitting and furnishings. Each AP specifies the scope, context, information requirements, representation of the application information, and conformance requirements. STEP goes beyond the Initial Graphics Exchange Specification (IGES) by defining the processes, information flows and functional requirements of an application. The definition and development of a STEP AP includes thoroughly documenting the information requirements and processes which support the application, understanding in detail the CAD and CAM systems, and developing a consensus within ISO. After acceptance, the ISO Central Secretariat handles publication. (10,58,79,81,85).

ESTEP (Evolution of STEP)-A team made up of American Bureau of Shipping; Atlantec Enterprise Solutions; Electric Boat Corporation; Intergraph Government Solutions, Intergraph Corporation; STEP Tools; Ingalls Shipbuilding; Litton Ship Systems Full Service Center; M. Information Engineering; and Naval Surface Warfare Center, Carderock Division-ESTEP is a task within ISE (see below) building upon the work of the MariSTEP consortium and the NIDDESC standards development efforts. The purpose of ESTEP is to validate product model standards for the shipbuilding industry, implement product model data translators, and to further the development of shipbuilding APs 216 (Moulded Forms), 218 (Ship Structure), and 227 (Plant Spatial Configuration) (86).

EMSA (European Maritime STEP Association)-A group of ship yards, software vendors, classification societies, ship owners, model basins and research institutes that is promoting and supporting technical development, deployment and industrial use of STEP within the European maritime sector (87,88).

SEASPRITE (Software Architectures for Ship Product Data Integration & Exchange)-A consortium that includes Lloyd's Register (United Kingdom), British Maritime Technology (United Kingdom), Kockums Computer Systems (now Tribon Solutions)(Sweden), Napa Oy (Finland), SINTEF (Norway), Odense Steel Shipyard (Denmark), Kvaerner Group (Norway), Vickers Shipbuilding & Engineering (United Kingdom), MARIN (Netherlands), Det Norske Veritas (Norway), and Instituto Superior Tecnico (Portugal)-:-Building on the results of previous projects, such as NEUTRABAS, MARITIME, Shipstep and Kactus, this project aims to develop a complete product model, define the information requirements for a data exchange and management architecture, and integrate the STEP product model application protocols. It is to provide European shipbuilders and their associates with a way to facilitate the reuse and migration of data throughout the ship life cycle (82,89,90).

MariSTEP-A team composed of United States members Avondale Industries, Bath Iron Works, Electric Boat Corporation, Computervision Corporation (since purchased by PTC), Ingalls Shipbuilding, Newport News Shipbuilding, the University of Michigan Transportation Research Institute and the Swedish company Kockums Computer Systems (now Tribon Solutions). This is a United States MARITECH project undertaken to implement product model data exchange capabilities among United States shipyards through a neutral file approach and to develop a United States marine industry prototype product model database (PMDB). The PMDB is to facilitate the implementation of translators and product model data architecture by United States shipyards and CAD system developers (83,91).

Manufacturers' Technical Information-The Marine Machinery Association and the United States Maritime Administration with assistance from the MARITECH program are developing methods of electronic commerce that will allow manufacturers to present technical information, prices and availability to the customer via computer. The project aims to:

- revise the standards of marine information,
- develop a standard technical information system,
- create electronic vendor catalogs, and
- research and improve electronic communication for the marine industry.

Information is to be made available first on CD-ROM and then on the Internet (89).

MARIS (Maritime Information Society), co-lead by the European Commission and Canada, is an organization designed to keep the international shipping industry updated (92). The major objectives of MARIS are to:

- establish a worldwide maritime information system,
- promote the operability and connectivity of existing information systems worldwide,
- demonstrate the possible benefits of maritime information technology, and
- support the worldwide standardization in the maritime sector.

ISE (Integrated Shipbuilding Environment)-A multi-year program carried out by a team of shipyards, design firms, a classification society, and academia. It is aN ational Shipbuilding Research Program (NSRP) Advanced Shipbuilding Enterprise (ASE) partnership between government and industry. ISE is focused on the development and validation of integrated product and process models to integrate the efforts of shipyard, designer, shipowner, marine supply chain, and classification society. ISE builds upon the lessons learned in previous MARITECH programs, including COMPASS and FIRST (93).

SHIIP (Shipbuilding Information Infrastructure Project)- This is another multi-company NSRP ASE partnership between government and industry. This shipyard initiative has the goal of supporting the integration of systems technologies within the U.S. shipbuilding industry through standards based protocols (94).

13.10 COMPUTER IMPLEMENTATION

13.10.1 General

Computer implementation involves two important deciSIOns:

1. whether to use computer based tools, and, if it is decided to use computer based tools, and
2. which tools to use.

To use or not to use computers, and to what extent, commonly involves a step into unknown territory and raises serious financial, organizational and corporate culture concerns. The process can feel threatening.

Fortunately, more and more examples exist of shipyards successfully implementing computer-based tools. Indeed, the trend is progressing from the large yards, which have had some sort of computer-based tools for decades, to mid-size and even small yards. However, computer tools and capabilities are always changing. As the programs and hardware change, the yards must change, if they are to remain competitive on the world market. The challenge of dealing with change is not a one-time event but rather a process itself. In the traditionally conservative shipbuilding industry, this is a serious challenge.

13.10.2 Program Selection

Each shipyard or design firm that considers purchasing new computer based tools or upgrading those tools already in place will make decisions that will determine, among other things, the level of sophistication of the programs; the costs of purchasing and maintaining the programs; user training; and whether certain design and construction processes must be changed. Ultimately, the decisions must be business based. In other words, the technology of the computer-based tools must align with the business objectives of the organization (95).

Thus, a selection methodology is needed. The details will vary by organization and by the type of programs being purchased. In general, the steps are as follows (see Figure 13.10) (5,7,95):

1. *Conduct business assessment:* The real objective of the organization is *business results*, so the organization's goals are first defined. This is commonly a task of top management and the results are stated in the form of a strategic plan, considering elements such as the following:

- market leadership goals,
- strategic direction of the organization,
- planned response to market needs,
- costs of implementing the programs,
- design and construction processes within the organization,
- relationships with suppliers and vendors, and
- relationships with customers.

2. *Define new processes:* New process or variations of existing processes will be necessary as a result of the new direction defined in Step 1. Old processes, even with new tools, will yield old results, or at best, less than optimum results. A clear understanding of the needed organizational changes is essential. It has been noted that the same programs will lead to different results if introduced into different organizational environments, and for success, substantial departmental changes may be necessary (41). Thus, the affected parts of the shipyard must be reorganized to meet the challenges of the new situation, with new problems, new focuses and new solutions. External consultants commonly are needed to guide this process of reorganization at the planning and implementation stages.

1. Conduct business assessment
⇓
2. Define new process
⇓
3. Identify priorities
⇓
4. Select requirements
⇓
5. Select program

Figure 13.10 Selection Methodology

It is important to define the whole project as cooperation among all personnel in the organization, from shop floor operators to top management.This will result in an atmosphere of shared ownership and help in gaining acceptance of the new situation and minimize resistance to necessary changes. Communication is essential. In addition, worker motivation and education must be addressed.

3. *Identify priorities:* Identify problem areas in design and construction processes. Eliminating or alleviating those problem areas will remove constraints from processes and improve efficiency.
4. *Select requirements:* Select appropriate requirements that will address the priorities of Step 3. Requirements for a CAD program will be different from those of a product model program; thus, the requirements must be tailored to the needs of the organization within the context of the computer-aided tools under consideration.
5. *Select program:* Using the requirements of Step 4 as a guide, a survey of available programs is carried out and the best program is selected. An alternative is to use the requirements of Step 4 as the basis for in-house development of a program. For any but the simplest program, this is usually not a wise option because of the high developmental costs of programs.

Again, the selection methodology is business driven and not technology driven. Organizations may be tempted to purchase new programs without thinking through the implications at the business level.

In conjunction with this selection methodology, organizations are well advised to ensure that the expectations of affected personnel are realistic. Changes in processes mean that changes in behavior and organization are often necessary. For example, product model programs may eliminate the need for a lofting department. Loftsmen may find themselves part of a design team or they may be shifted to production.

In either new role, the experience gained in the lofting department would be applied to a part of a new process. The loftsmen would be expected to learn and contribute to the new process and understand that it is different from the process they had participated in prior to the adaptation of the product model program. Generally, everyone involved in computer based tool changes must be aware of the expectations placed upon them, from top management to shop personnel.

The implementation of any but the most focused and simple computer programs can be complicated and time consuming. Implementation of a CIM system can be quite complicated. Detailed knowledge and experience are required to tune the system and the organization to best potential. An implementation period is required, and its length and cost should not be underestimated (5,7).

Finally, the new computer programs must be managed. Usually there are opportunities for improving a process or improving the program to enhance its value to the organization. Owning and using all but the simplest computer based tools is an ongoing process of refinement.

13.10.3 Selecting Requirements for a CAD/CAM/CIM Program

Selecting requirements (Step 4 of the selection process described in the preceding section) is deciding "what" the computer system must be capable of doing for a particular organization. It is tempting to skip Step 4 and proceed directly to Step 5 and review candidate computer programs. However, selecting programs prior to deciding exactly what is required can result in confusion and increase the probability of purchasing a system that will not prove to be satisfactory. This said, selecting requirements is a daunting task. The following paragraphs attempt to make the task at least practical by outlining a requirement selection process.

First, a word about the definition of requirements. Requirements are not to be thought of as comprising modules of, for example, a product model program. Rather, requirements should be thought of as features, which are to be found within a program.

Again, the requirements do not tell how to design the program, they simply state the needs the software must fulfill: what the program must be capable of doing. Thus, various programs may exist, each of which may meet the requirements, but in different ways. In many cases there is not a *right* solution, but several candidates, each with strengths and weaknesses.

As part of a National Shipbuilding Research Program Project, a set of requirements was developed for a future-oriented product model program (5). The requirements were organized to be consistent with United States shipyard typical practices. All requirements were first grouped into the general areas of Design, Production, Operations Management and Umbrella, as shown in Table 13.111.

Initially, a detail area entitled *Quality Control and Assurance, SQC* was included under Operations Management. The final version of the requirements omits specific quality requirements, opting to make quality inherent in the overall system, much in the manner of European and Japanese shipyards.

The full list of requirements is shown in Table 13. IV, grouped in the two-tier manner presented above. These requirements may serve as the basis for defining what a product model program must do for a shipyard or design firm. Depending on the needs of the organization, some requirements may be added and others omitted from this list. Further details of each requirement are provided in (5).

TABLE 13.11I Future Requirements for Product Model Program

General Area	*Requirement*
Design	• Conceptual/Preliminary Design • Functional Design • Detailed Design
Production	• Fabrication Processes • Joining and Assembly • Material Control • Testing and Inspection
Operations Management	• High-Level Resource Planning and Scheduling • Production Engineering • Purchasing/Procurements • Shop Floor Resource Planning and Scheduling
Umbrella	• Umbrella

13.10.4 Example Using Selection Methodology

The following paragraphs present a hypothetical example of how to use the five-step selection methodology presented above, including the selection of requirements:

1. *Conduct business assessment:* In this example, the organization is in the market of designing and constructing high-speed aluminum ferries to transport passengers and vehicles between ports over potentially rough waters, such as those of the North Sea. The organization is well established in the high-speed ferry market and has earned a good reputation for its willingness to customize ferries for the needs of each owner. The organization's top management has discussed how to improve business results. Discussion has revealed that the competition, which in the past only offered stock designs, is now successfully customizing its ferries. Thus, a previous market advantage, willingness to customize, has been compromised. Top management decides on a strategy of optimization to regain their overall business advantage. They understand that high-speed ferries are weight critical, and decide to optimize ferry structural weight in their ferry designs. In this case, *optimize* means *minimize structural weight, while maintaining strength to safely meet design loading.*
2. *Define new process:* Investigation shows that significant weight savings cannot be achieved as part of the existing shipyard production process. Production simply cuts the parts as defined by the design, and there is no opportunity for decreasing weight at this stage. Thus, the focus turns to design. The organization's present design approach uses classification society rules to generate structural designs. Engineering and design management point out that this rules-based approach provides little opportunity for future weight savings, and they set about finding a new process that will enable the organization to optimize the structural weight. The new process is defined as *computational engineering methodology.*
3. *Identify priorities:* Personnel from engineering and design management note that manual optimization processes are too time consuming to be practical. Manual optimization would hold up the design process as a whole. Thus, the organization identifies the need for a computer-based approach as its priority.
4. *Select requirements:* Two requirements (from among those listed in the preceding section) address the priority of optimizing structural weight when switching from a rules-based process to a computational engineering process. The two requirements are: i) *Concept/Preliminary Design Engineering Analysis Tools:* This requirement addresses engineering tools to assist in structural analysis (including optimization), such as hull girder analysis, finite element analysis, and weights and centers calculations, and ii) *Detail Design Engineering Analysis Tools:* This requirement addresses the subject of dynamic hull loading and fatigue analysis. Fatigue analysis is an attractive feature to the organization, because its ferries are constructed of aluminum, which is subject to fatigue, especially in rough waters. Through study of relevant technical literature associated with the requirements, the organization becomes familiar with the present state of the art and the structural optimization programs on the market.
5. *Select program:* The organization contacts vendors and selects the program and hardware most suited for its own weight optimization process for its aluminum ferries. As part of this process, the organization opens a dialogue with the classification societies and ensures that the proposed program is acceptable to the classification society.

Typical considerations relevant to the selection process include determining the following:

- what specific features are necessary or desired for the selected software,

TABLE 13.1V Full List of Future Requirements for Product Model Program

Design: Conceptual/Preliminary Design

1. Concept/Preliminary Design Engineering Analysis Tools
2. Reusable Product Model
3. Develop Initial Build Strategy, Cost and Schedule Estimates
4. Classification/Regulatory Body and Owner Compliance Support

Design: Functional Design

5. Connectivity Among Objects
6. Tools to Develop Standard Parts, Endcuts, Cutouts and Connections

Design: Detailed Design

7. Automated Documentation
8. Detail Design Engineering Analysis Tools
9. Design for Fabrication, Assembly and Erection
10. Linkage to Fabrication Assembly and Erection
11. Automatic Part Numbering
12. Interference Checking
13. Linkage to Bill of Material and Procurement
14. Weld Design Capability
15. Coating Specification Development
16. Definition of Interim Products
17. Consideration of Dimensional Tolerances
18. Context-Sensitive Data Representations

Production: Fabrication Processes

19. Processes to Cut/Form Structural Plates and Shapes
20. Documentation of Production Processes
21. Information Links to Production Work Centers
22. Piece and Part Labeling
23. Creation of Path or Process Programs for NC Machines and Robots
24. Development of Interim Product Fabrication Instructions
25. Simulation of Fabrication Sequences

Production: Joining and Assembly Processes

26. NC Programs for Joining and Assembly
27. Automated Subassembly/Assembly Processes
28. Programmable Welding Stations and Robotic Welding Machines
29. Locations Marking for Welded Attachments
30. Definition of Fit-Up Tolerances
31. Control of Welding to Minimize Shrinkage and Distortion
32. Programming for Automated Processes
33. Definition of Fit-Up Tolerances for Block Assembly Joints

Production: Material Control

34. Capabilities for Material Pick Lists, Marshalling, Kitting and Tracking
35. Tracking of PiecelParts Through Fabrication and Assembly
36. Communication of Staging and Palletizing Requirements to Suppliers
37. Documentation of Assembly and Subassembly Movement
38. Handling and Staging of In-Process and Completed Parts

Production: Testing and Inspection Guidelines

39. Testing and Inspection Guidelines

Operations Management: High-Level Resource Planning and Scheduling

40. High Level Development of Build Strategy
41. Order Generation and Tracking
42. Performance Measurement
43. Production Status Tracking and Feedback
44. Inventory Control
45. High Level Planning and Scheduling

Operations Management: Production Engineering

46. Development of Production Packages
47. Development of Unit Handling Documentation
48. Parts Nesting
49. Development and Issue of Work Orders and Shop Information

Operations Management: Purchasing/Procurement

50. Material Management

Operations Management: Shop Floor Resource Planning and Scheduling

51. Provision of Planning and Scheduling Information to Shops
52. Work Order/Work Station Tracking and Control
53. Detailed Capacity Planning for Shops and Areas
54. Collect and Calculate Costs for a Major Assembly

Umbrella: Umbrella

55. Datacentric Architecture
56. Computer-Automated as Well as Computer-Aided
57. Interoperability of Software
58. Open Software Architecture
59. Accessible Database Architecture
60. Remote Networking Capability
61. Full Data Access (Read Only) to All Project Participants
62. Assignment of Data Ownership
63. User-Friendliness
64. Enterprise Product Model
65. Integration With Simulation
66. Information Management
67. Scalability
68. Transportability
69. Configuration Management
70. Compliance With Data Exchange Standards.

- what hardware and program configurations are suitable for integration with the organization's existing system, and
- what start-up time and cost factors are drivers, for example, training?

1111 FUTURE TRENDS

13.11.1 General

As previously mentioned, the field of computer-based tools is one of constant change. While change cannot be predicted with certainty, there are a number of trends, described in the following paragraphs, which give indications as to directions of future enhancements in the field.

13.11.2 Simulation

Simulation uses computers to mimic and predict processes of design, production and operation outside of the real-world constraints of space and time. Instead of waiting seven to ten years to test a new naval combatant prototype, for example, a simulation would be developed in a fraction of that time, modeling design, production and operation of the ship (7,96,97).

Design, production and operation simulation techniques, already in use to a limited extent, are expected to increase in functionality and sophistication in coming years. Presently, this technology is used mainly by the defense industry; future trends are expected to include a jump in use in the commercial arena. Simulation technology is improving through higher-performance hardware, lower hardware prices, development of standards (often de facto), and improved software products (98).

Design simulation, utilizes virtual reality (adding movement and animation to the product model) to enable users to "walk through" the interior and exterior of a ship. Design dimensions, geometries, attributes and arrangements may be viewed and checked without the traditional need to construct a physical model. The user may view the ship on a computer monitor or by means of more immersive virtual reality techniques such as head-mounted displays, stereo glasses or an immersive workbench (29,98).

An example of design simulation is found in the U.S. Navy's New Attack Submarine Program, being carried out by Electric Boat Corporation and Newport News Shipbuilding. Simulation programs mimic and predict processes of design, production and operation for the complex nuclear-powered submarine. Design dimensions, geometries and arrangements are viewed and checked without the traditional need to construct a physical model of plastic and wood. **In** addition, production simulation allows management to predict the effectiveness of processes and combinations of processes in the two shipyards, helping to make a smooth transition between design and production. Great savings are realized in this integrated process. For instance, the quantity of different part numbers on the *Seawolf* submarine, designed by Electric Boat and Newport News shipbuilding uses on the order of 100 000. On the New Attack Submarine, there are projected to be 12000 parts, a reduction by nearly an order of magnitude.

Production simulation allows management to predict the effectiveness of processes and combinations of processes in the shipyard. Production simulation is most frequently used in industries involved in mass production. Such industries often have a streamlined production, repetitive operations and well-defined products. This is not the case in shipbuilding, which can be characterized by:

- one-off or relatively small series production,
- many different work disciplines,
- large number of different work tasks,
- high degree of manual work, and
- work activities difficult to identify and quantify.

Thus, with production processes more complicated and production parameters more difficult to quantify, production simulation is not as far along in the shipbuilding industry as in certain other industries. **In** shipbuilding, production simulation may include the shipbuilding process, in which assembly and schedule are simulated (for example, robotic welding) (7,37).

Operation simulation enables the user to test the ship, and variations of the ship, as it is intended to be used, in a realistic environment with real humans at the controls. Using operation simulation as a guide, the design may be refined to better meet the needs of the customer. This approach has been successfully demonstrated, an example being the design of a bridge for a frigate (96,99).

13.11.3 Enhanced Communication

For enhanced communication among product model programs, STEP may be the most promising alternative, because of the high degree of international cooperation being focused on its development.

Enhanced communication among shipyards, vendors, design firms and classification societies may be achieved through closer working relationships, enhanced software and improved Electronic Data Interchange (EDI) remote networking capabilities (5,100). The Internet is likely to be increasingly used as a way to exchange data. For example, designers could drag standard parts from suppliers' on-line catalogues and drop them directly into their standard designs (101).

Related to the element of enhanced communication is the capability to use several programs in concert to address a design task. For example, a CAD program may be used with a spreadsheet program, taking advantage of features such as linking and cut-and-paste (5).

13.11.4 Portability

Portability is the ability to use a program on several different hardware platforms. The term portable implies that the software is intended for several platforms from inception and that this factor is considered throughout the design and implementation of the program. Portability is different from porting or migration. These involve making an existing program run successfully on a new platform and can often result in replacing one set of code with another (58).

13.11.5 User Friendliness

The program is easy to learn and to use, with features such as carefully designed graphical user interfaces, seamless integration of program modules into a conceptual whole, immediate feedback, and a *natural* program operation. Advances in AI are expected to enhance user friendliness in areas such as spoken-language human-computer interfaces and natural language technology (5,102).

13.11.6 Expansion of Program Scope

Programs may be further extended beyond the narrow ship design limits traditionally set, and encompass areas such as production, cost estimation and program management. This expansion is either through in-house software development and addition to the baseline program or by links to second party programs.

An example of expansion is for a product model to include sophisticated document management capabilities, including vendor data. Another example is the ability to model ships outside of the purely graphics environment, for example, by developing a relationship between an engine and its volume, weight and output power, and thus assist in reducing design time through enhancing concurrent engineering (5).

Another example is development of capabilities to automatically route piping and electrical lines and arrange their associated components in a 3D shipboard design environment. Included is the capability for optimization for cost or other functions (103). A final example is automatic optimization of ship hull forms based on CFD (24).

13.11.7 Object-Oriented Programming

Object-oriented programming (OOP) is emerging as a popular choice for developing programs that are centered on the development, management and sharing of data. In this context, objects are pieces of code that are self-contained in a way similar to that in which sub-routines are self-contained in procedural computer languages. Examples of OOP languages include Simula, SmallTalk and Java (12,13).

An Object-Oriented Database (OODB) contains objects that possess attributes of almost any nature. The database manager can query the information carried by the objects, and new information can be attached to objects. OODBs offer a powerful way to store complex data structures (such as those of an entire ship). The object-oriented structure allows programmers to build programs in a highly modular way with abstract data types. Thus, changes to a program normally involve only one or several objects and not (as is often the case in procedural computer programming) extensive or wide-ranging re-writing.

The use of expert systems and the OODB approach to product modeling is aimed at facilitating the development of designs consistent with producibility considerations, beginning at the early stages of the design process.

13.11.8 ArtificialIntelligence

Artificial Intelligence (AI) traditionally has focused on developing programs that do what humans do. While this is still an aim in AI programs, other aims have been developed as well that can improve ship design and construction. AI of the future may (12,102):

- enhance machine vision systems for gauging, guiding and inspecting during the manufacturing process,
- improve intra- and internet systems to simplify the presentation of large amounts of information,
- assist the development of spoken-language human-computer capabilities,
- enhance robotic systems, including robotic vision systems, and
- help improve shipyard production process planning.

13.11.9 Ship Life-cycle Data Support

Certain ship owners, such as the United States Navy, maintain control of the entire life of their ships, from initial design and construction through an operational period that may last upwards of 50 years. Unlike most commercial owners, the Navy often alters its ships to keep pace with advances in technology and changes in mission requirements. In order to maintain a knowledge base of all ship-related data and keep control of a ship's configuration, the Navy is refining an approach called Integrated Product Data Environment (IPDE). IPDE is "an information system capability that supports the integration of a central product model database, associated data products such as drawings, technical manuals, training materials, and program execution information such as plans, schedules, and procedures in order to satisfy the data requirements of both contractor and Government users. The environment features the capability to concurrently develop, access, capture and re-use data in electronic form in a fashion that assures data integrity, efficiency and configuration control" (104).

13.11.10 Virtual Partnerships

A natural extension of improved communication among shipyards, regulatory agencies and vendors is the concept of virtual partnerships. Direct strategic partnering links, such as those between Alcoa and Northrop Grumman in the aircraft industry, have reduced cycle time between ordering and delivering. The stability inherent in such partnerships can lead to other benefits, such as predictable business loading. This in turn can enable suppliers to buy more efficient tooling, benefiting shipyard and vendor alike with lower costs. Communication is greatly enhanced through the use of advanced technology, enabling partners to share many types of design, production, management and procurement data. This advanced and high level of electronic communication is called electronic data interchange (EDI)(72, 105).

13.11.12 Overall Trends

Looking to the next five years and beyond, trends indicate that:

- software will increase in capability to take advantage of existing and future computing power,
- the use of computer aided ship design will take a firm hold in mid-size shipyards and in advanced small yards,
- ship designers will be more highly trained and their productivity will increase dramatically through the use of advanced computer-aided tools, and
- ship production needs will drive the ship design process.

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CHAPTER 14'

Design/Production Integration

Thomas Lamb

14.1 INTRODUCTION

It is hard to conceive that anyone would deliberately design something that could not be built. Yet the author has seen many cases of ship design that either could not be manufactured as designed, or else was very costly to build. That this situation is even broader than shipbuilding can be seen from the proliferation of Design for X, where X can be Manufacturing, Production, Assembly, Maintenance, etc. In the United States this resulted, in part, through the introduction of *Scientific Management* by engineers such as Taylor (1) and Fayol (2), who persuaded managers to organize their companies into specialized units and to even specialized skills within the units. While this was successful in many industries with many repetitive tasks at that time, and it has been credited with the rise of mass production and the great increase in U.S. productivity in the early 20th century, it also resulted in the current lack of design/production integration.

Design with a production friendly focus is not unique to shipbuilding. Design for Assembly (DFA) has been applied to other industries, particularly the automotive industry for many years. It has been credited with significant benefit and improvement in performance. A well known book on DFA is by Dewhurst et al (3). They identified eight guidelines including the order of importance as follows:

1. reduce part count and part types,
2. strive to eliminate fitup/adjustments,
3. design parts to be self-aligning and self-locating,
4. ensure adequate access and unrestricted vision,
5. ensure the ease of handling parts from bulk,
6. minimize the need for reorientations during assembly,
7. design parts that cannot be installed incorrectly, and
8. maximize part symmetry if possible or make parts obviously asymmetrical. The similarity with the DFP guidelines can be seen from the list in subsection 14.3.1.

The author contrasted the two extremes of design/production integration as *Isolated Engineering* and *Integrated Engineering* a long time ago (4). Today they would be called *Stove Pipe Operation* and *Concurrent Engineering (CE)* (see Chapter 5 - The Ship Design Process).

The improvement claims for CE and Integrated Product and Process Development (lPPD), such as 30% improvement in productivity and 50% improvement in build cycle; show just how bad an impact this lack of integration has had on companies and industries over the past 50 years.

British Shipbuilders found that they had a problem in having their designers adequately consider the production needs for their designs and prepared a formal *Design for Production (DFP) Manual* (5) in the 1970s. The U.S. had this problem as well and had A&P Appledore prepare a *Production Guidance Manual* for bulk carriers (6), in 1980, and the first conference on DFP was held at the University of Southampton in 1984 (7). Unfortunately it was too late to save *British Shipbuilders*. However, some of the developers of the original manuals became consultants and eventually prepared *Designfor Production Manuals* for the U.S. (8,9). In 1987 the author prepared a book for the NSRP titled *Engineeringfor Ship Production* (10), which described the need for design/production integration and the application of DFP.

That this subject was of prime concern to the U.S. shipbuilding industry can be seen from the forming of one of the National Shipbuilding Research Program panels as the SP-4 DesignlProduction Integration Panel. This panel ceased its operation in 1998 when the NSRP was reorganized to fit in the new NSRP-Advanced Shipbuilding Enterprise (ASE). However, the subject has remained in the forefront of the concerns of two new panels, namely the *Product Design and Materials Technologies* and the *Shipyard Production Process Technologies* panels.

Design/production integration includes the following concepts:

- focus on Design for Production (DFP)
- preparation of all design/engineering information in the most suitable way for Production,
- feedback of needs/preferences from Production to Engmeenng,
- direct communication and collaboration between Engineering and Production,
- providing each other with the knowledge and information they require to do the best possible job for each other,
- establishing the best information transfer between them thus eliminating unnecessary reworking of the information by Production to suit their needs, and
- standardization and documentation of processes, information flow, and all relevant attributes of the interim products.

These can be seen in the following current shipbuilding practices:

- use of 3-D product model as design/ production integrator,
- Product-oriented Work Breakdown Structures (PWBS),
- intermediate product catalogs/databases,
- development of Shipbuilding Policies,
- use of Build Strategies,
- preparation of engineering as workstation information packages,
- use of Concurrent Engineering and associated teams to ensure design/production integration, and
- the use of design and build plans by the most recent design/planning teams for proposed new U.S. Navy programs.

Concurrent Engineering is briefly discussed in Chapter 5 - Ship Design Process. It is covered in greater detail in references 11 to 13. This chapter will only address it in the way it enables design/production integration. This chapter will focus on DFP and how engineering should be prepared to b~st suit and support production and a number of approaches that can assist/enable this to happen.

The integration of design and production depends on a great amount of information. Today, this is enabled through the use of 3-D product models and different inforrrtation technology systems. Some Computer Aided Design (CAD) systems, used by shipbuilders, provide most of the required capability, but have not yet reached the totally integrated system or Computer Integrated Manufacturing (CIM).

14.2 ENGINEERING APPROACH

The format of engineering information, including the content of drawings, has developed over many years. Changes and improvements have occurred very slowly, and in some shipyards and design offices, not at all. Traditionally, shipyards were craft-organized and only required the minimum number of drawings for which accuracy was not essential. The loft prepared the templates and made everyday decisions on structural details. The pipefitters worked from diagrammatics and developed their own pipe templates from the ship being built. This system was also true for the other shipyard crafts.

The changeover from a traditional craft-organized shipyard to one of advanced technology has obviously had a tremendous effect on all shipyard departments. It should have had its second greatest impact on the engineering department. However, many engineering departments did not rise to this challenge and, therefore, lost what might have been a lead position for directing and controlling change. Engineering simply ignored the needed changes and left them to be incorporated into the shipbuilding process after their work was completed in the traditional manner. Shipyards responded to this problem by getting the necessary production information from other sources, usually new groups that may have been called *industrial* or *production engineering* or perhaps from an existing planning group. Some shipyards even accepted the fact that engineering information was inadequate for production and left it to production workers to perform as best they could. This situation often resulted in the same work being done many times before it was reluctantly accepted by the inspectors.

Production performance depends largely on the quality, quantity, and suitability of technical information supplied by engineering. By organizing for integrated engineering and preparing design and engineering for zone construction, engineering can take its proper place and play an essential role in the improvement of shipbuilding performance. This section discusses how this can be done, but first considers what is production-compatible engineering (integrated engineering) by comparing it with traditional engineering.

14.2.1 Traditional Engineering

Usually all the visual information used by a shipyard production department today is not prepared solely by the engineering department. Most shipyards still have various preparation phases divided in a way developed and used 30 to 40 years ago. At that time, the following division oflabor made sense because of the methods used:

- Engineering
  - design and working drawings
- Loft
  - full-size fairing of lines
  - layout of structural parts
  - template construction
- Pipefitters
  - pipe templates and sketches
- Sheet metal workers
  - layouts, developments, and templates
- Shipwrights
  - full-scale layout on ship

However, most shipyards have been improving their production processes for years, and their information needs have changed during that time. Some shipyards utilize structural block construction, pre-outfitting, advanced outfitting and, more recently, zone construction. To perform these tasks from traditional engineering is not impossible, but it requires additional planning and even more design and engineering to be prepared after traditional engineering is complete. This system obviously involves wasted effort, additional man-hours and does not assist the move to short build time.

The preparation of traditional engineering structural drawings has really not advanced much from the days .of the iron ship. That is, they still prepare structural drawiQ.gs as item drawings, such as tank top, shell plating or expansion, decks, bulkheads, and frames.

Traditional engineering piping drawings are for individual systems for the complete ship. They mayor may not show pipe breaks, hangers, and some production-added information. The same is true for HVAC and electrical, except that electrical drawings are sometimes little more than pictorial concepts with no locating dimensions for equipment.

Usually interference control in traditional engineering is provided by space composites, although engineering models are also used extensively for this purpose. A major problem with this approach is that in some shipyards the electrical crafts go ahead and complete their *hot work* before many of the other detailed systems and composites are completed. The work is performed in the easiest location without checking it or even feeding it back to engineering to locate it in the composites. Apparent production work progress is achieved early in the project, and everyone is happy until the interference problems start and extensive rework is required. This problem is avoided in those shipyards that utilize 3-D product models in which the electrical system is included

Traditional engineering usually includes the bills of material on the drawings or as a sheet of a multi-sheet drawing. It also makes use of large drawings, often up to 4 m in length. Figure 14.1 graphically portrays the problem this system creates on the ship compared to the smaller sheets of

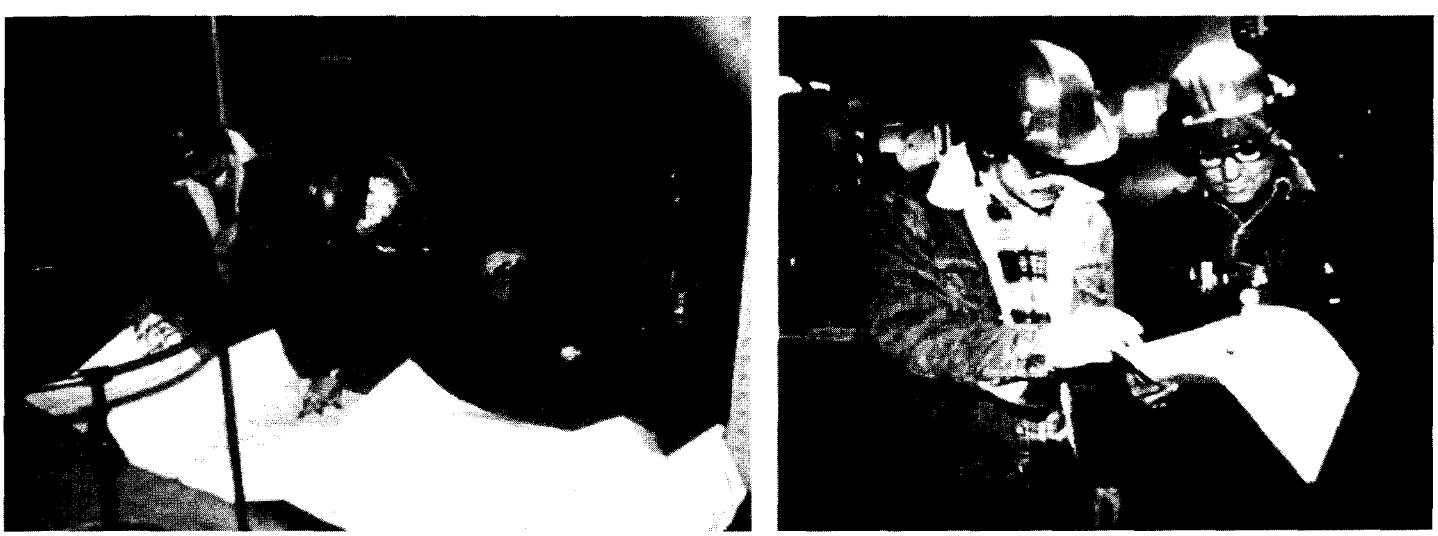


Figure 14.1 Large Drawing Handling Problem

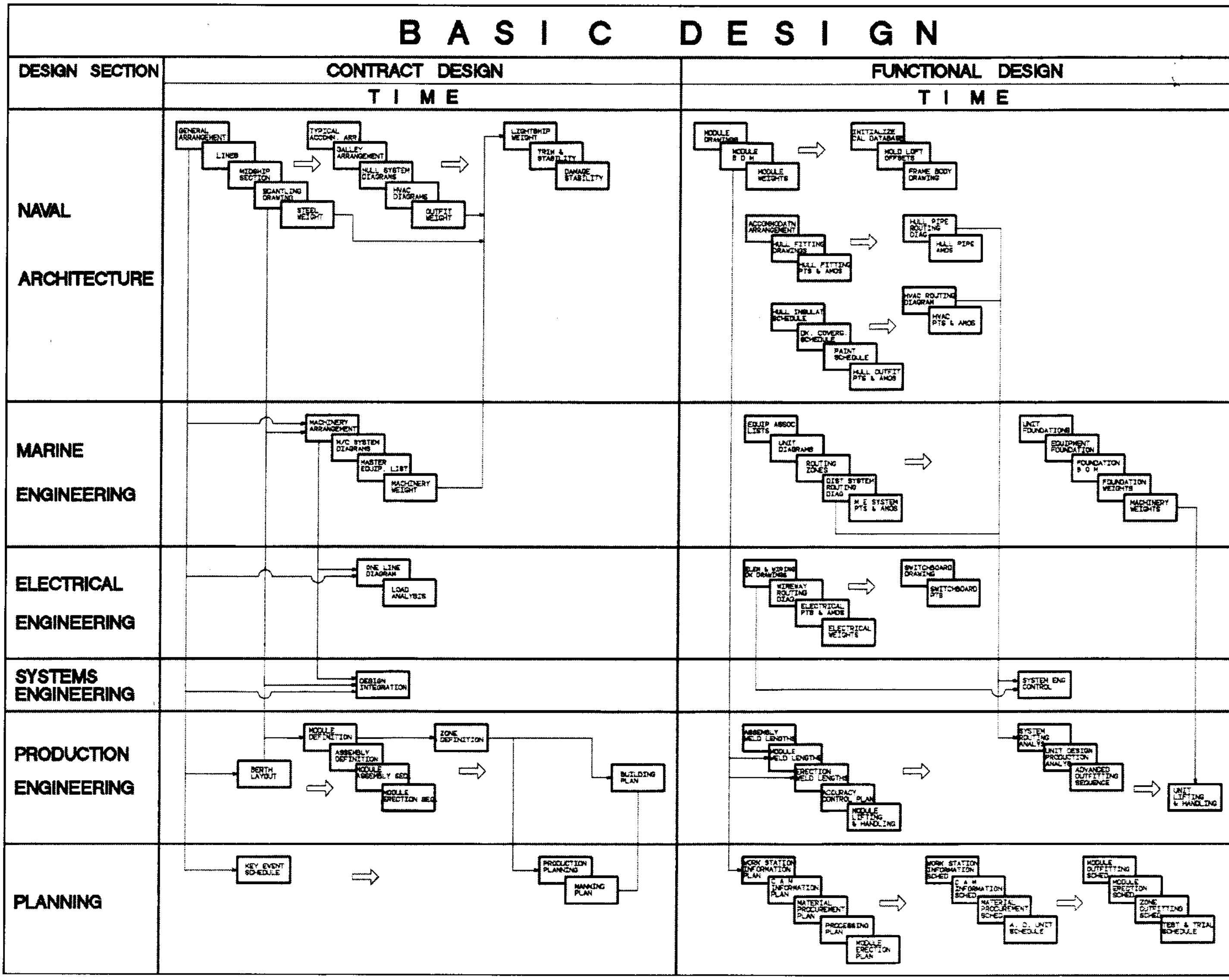


Figure 14.2 Basic Design Process Flow

the proposed Engineering for Ship Production booklet. Since each drawing is for the total ship, but is required each time part of it is used in each module or zone, the drawing must be printed and issued many times, resulting in wasted paper and duplicated effort. Also when reissued because of a revision, planning and production must spend time to determine how many modules or zones are impacted by the reVISIOn.

Traditional engineering drawings contain little production-required information such as module weights, module breaks, system breaks, lifting pad locations, bolting torque, pipe hanger locations, system testing, tolerances, and quality requirements.

Some shipyards attempt to provide some of this information on traditional engineering drawings by having prints of the drawings marked up with production data by the planning/production control groups for incorporation into the original drawings before formal issue. Others provide the required production information on unique additional documents to the traditional engineering drawings.

The traditional engineering practice of referencing drawings, ship specification, standard specifications, and other data on the drawing, instead of including the information, is a serious problem to production. To expect production workers or even their supervisors to have access and knowledge of the references is impractical. Because of this situation, items are often ignored and the work is not *done to spec.*

Traditional engineering is not suitable for high productivity, short-build cycle shipbuilding, and therefore has no

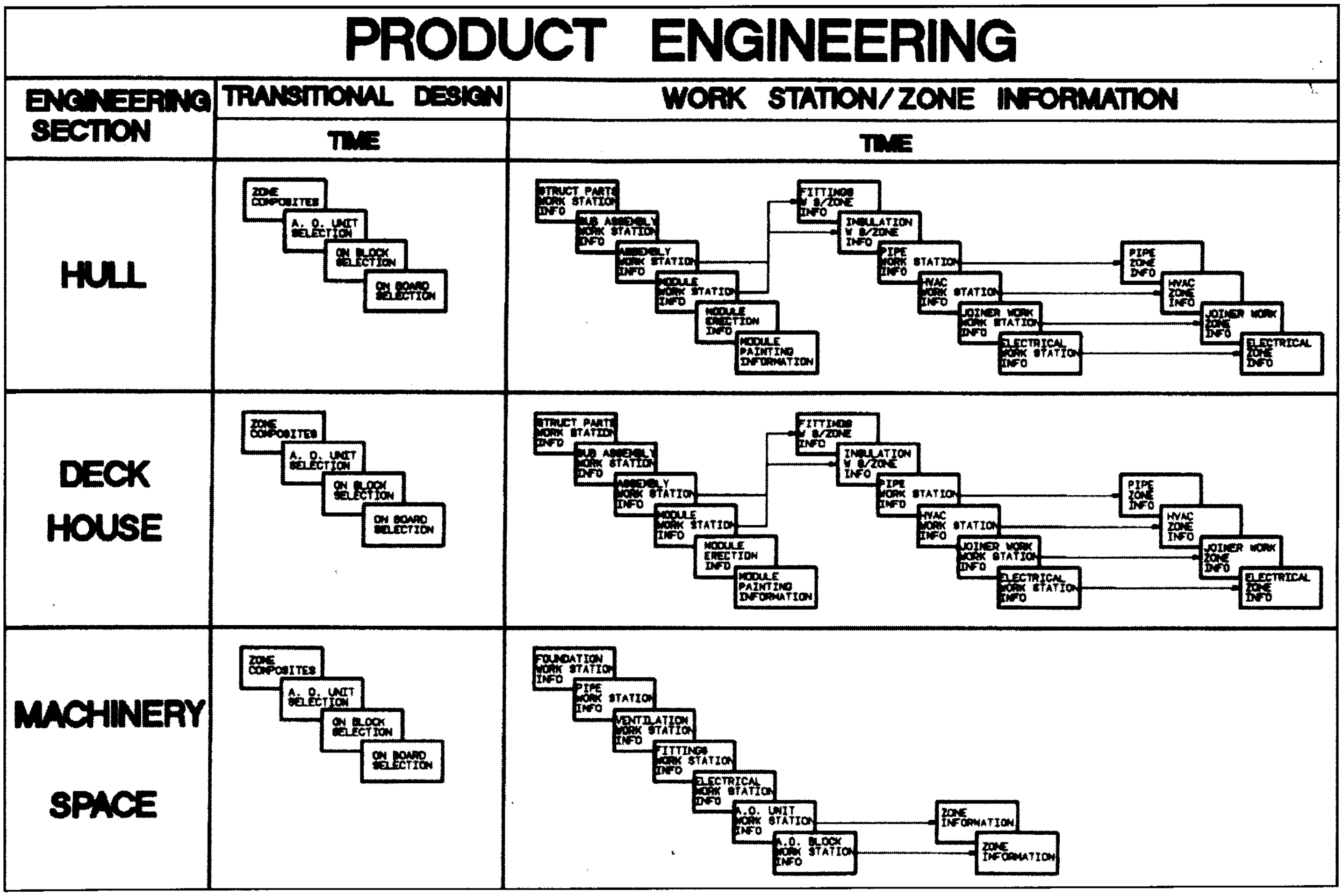


Figure 14.3 Product Engineering Process Flow

place in today's struggle to maintain some semblance of' competitive shipbuilding.

14.2.2 Production-compatible Engineering

The first break from the traditional systems drawings occurred when some shipyards introduced structural block drawings. The next stage was the use of subassembly, assembly, and module-sequenced drawings, but these were initially prepared in addition to the structural module drawings.

Next, the outfit drawings were prepared for zones. Finally, pipe sketches or drawings for pipe assemblies were prepared by engineering, first manually and later by computer-aided design.

Currently computer-aided design/computer-aided manufacturing is being used to provide production information for both pipe and sheet metal products. Today the goal for optimum data transmittal is to have an engineering information package for each workstation (including zones Onboard the ship). This is not only for structure, but also for all other material and equipment. A work station drawing shows all the work that occurs at one location, either shop or ship zone. It can be one sheet showing the completed product at the end of all work at a given work station with written sequence instructions, or it can be a booklet of drawings (see Figure 14.1) showing the sequenced buildup for the product from its received status to its completed status for the work station.

This process of design and engineering is integrated with construction planning and is in constant participation and communication with the production department. This integration can be seen in Figure 14.2, which shows the process flow during contract and functional design. Figure 14.3 shows the process flow during transitional design and work station/ zone information preparation. Note that all planning is completed during contract and functional design and in the proposed approach this includes advanced outfitting planning.

The use of the Build Strategy Approach, with its Shipbuilding Policy and Build Strategies, is a very effective if not essential tool to the proposed engineering approach (14,15). It is further beneficial if all manufactured and purchased material to construct the ship is categorized within a standard classification system (product definition). If the production methods to be used (product processes) are defined, workstations can be decided.

All this information will be contained in the Shipbuilding Policy to be used by engineers and planners when preparing the contract design and the building plan. The product definition can be based on a group technology classification and coding system, or it can be a simple listing of major product. The product processes will be based on a process analysis for each product and the available workstations. It is easy to see that this is a worthwhile tradeoff.

Suggestions on how engineering can best be provided to the production department will be presented for each of the individual groups within the engineering department, even though it is obvious that standardization of data preparation is the ultimate goal.

14.2.3 Benefit

With the traditional engineering approach, construction cannot be started until a number of item drawings are complete (Figure 14.4). In an actual case, one block required 13 drawings to be completed before the block could be lofted. With the zone approach, construction can commence when the first block drawing is complete (Figure 14.5). Also, it is necessary for someone (production planning) to prepare block parts lists and sequence assembly sketches.

With the zone approach, production can use engineering prepared drawings directly, thus saving additional effort and time. On-unit advanced outfitting has been demonstrated to be a significant productivity improver.

By integrating all system diagrammatics in a given space, the grouping for piping of various systems can be considered. Also, knowing that the diagrammatics are more accurate allows material to be ordered with greater confidence, which reduces the need for margins. More complete diagrammatics are acceptable for complete owner and classification approval; that is, it is not necessary to send detailed production drawings for approval.

14.2.4 Transitional Design

The transitional design can be likened to building a prototype, except that it is constructed on paper. If CAD is used, the prototype is effectively modeled in the computer. The most important task in transitional design is the selection of the zone/subzone breakdown for the design effort. For example, a subzone could be a compartment surrounded on all sides by major structural divisions, such as deck/flat/tank top, transverse bulkheads, side shell, and longitudinal bulkheads.

Zone design arrangements are similar to the traditional composites. However, they are prepared from distribution system routing diagrammatics developed during functional design. The traditional composites are prepared from completed system arrangement and detail drawings. Traditional composites are drawn as an interference-checking tool and, for this purpose, are slices through the compartment, showing only the items in the immediate layer below. Zone design arrangements show all the visible items seen from the viewing plane. All products should be included no matter their size. The traditional engineering practice of excluding pipe below 40 mm diameter is no longer acceptable. When the zone design arrangements are prepared manually, the backgrounds can be provided by the Computer-aided Lofting (CAL) system. Manually prepared zone design arrangements could be drawn with single line pipe representation. However, it is preferred to show double line, including insulation where appropriate. Once the zone design arrangement is completed, the products are identified as follows: zone or unit, pipe assembly, vent assembly, wireway, foundation, and floor plate group.

The required zone/unit material quantity is also developed at this time. By accumulating the material quantities as zone design arrangements are prepared and deducting the material from advance material orders, effective material ordering control is possible. A list of all the products in a zone/subzone provides an accurate compartment check off list.

Obviously, during the preparation of zone design arrangements, all systems are developed for interference avoidance and checked for interference as the work progresses.

It should be obvious that the use of CAD for this design phase has many advantages. Three-dimensional solid modeling CAD systems enable a true prototype to be modeled and all working, maintenance, and access requirements to be checked prior to any construction.

14.2.5 Workstation/Zone Information

Many successful shipyards claim that their success is based on better work organization. This is accomplished through better planning and better instructions/information and work packages. The work package concept is the division of a total task into many work packages for small tasks. A typical guide is that a work package should be as follows.

- 2-week duration maximum;
- 200 hours of work maximum;

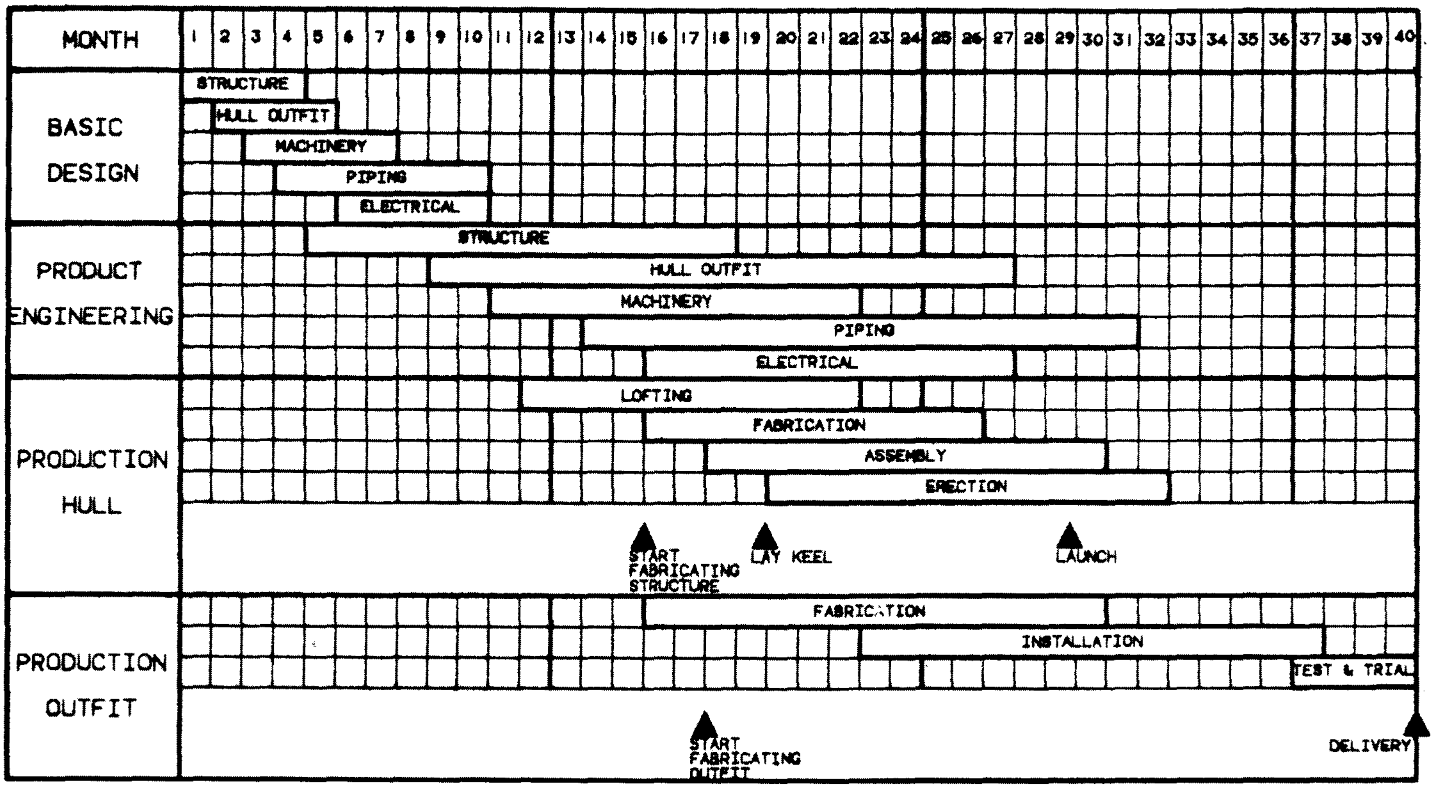


Figure 14.4 Traditional Detailed Design and Construction Appoach Time Cycle

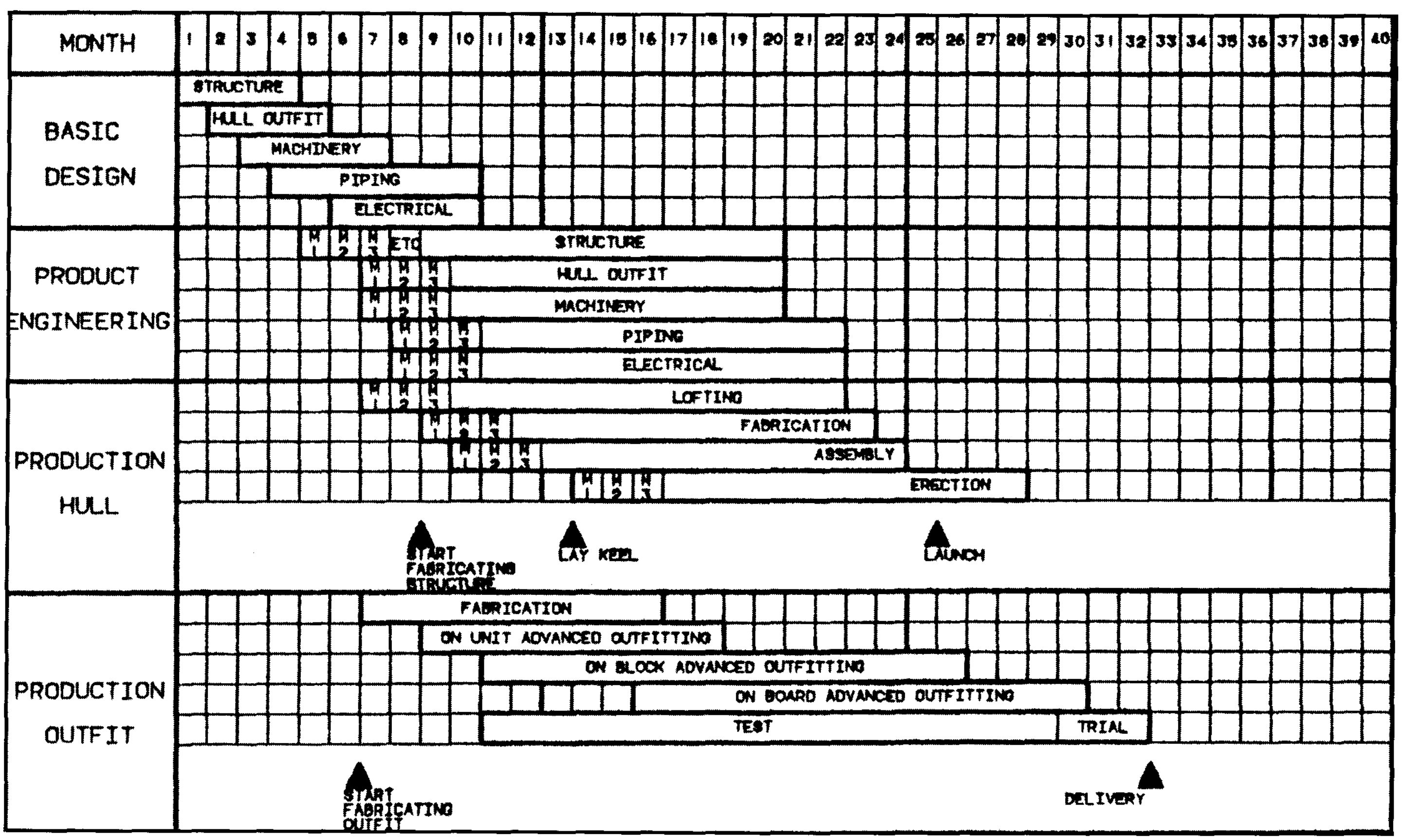


Figure 14.5 Block and Zone Approach Time Cycle

- work for a maximum of three workers;
- include only (but all) the information required by workers to complete the work package tasks, including drawings, parts lists, and work instructions; and
- include production aids such as N/C documentation, templates, and marking tapes.

The first three items are difficult to adhere to for certain shipbuilding tasks on the berth but are achievable for most shop work.

Engineering can effectively participate in preparing some of this information and, in doing so, eliminate a lot of current duplication of effort. Planning will select the tasks to meet the first three requirements. Engineering can prepare the information covered in the last two.

For this approach, it is proposed that separate workstation information be prepared for each work package. Workstation information should be prepared on the following basis:

- information should show only that necessary for a given workstation.
- information should consist of sketches and parts list.
- complete information for the tasks must be given.
- no referencing allowable.
- separate work packages should be prepared for each craft (trade). Sketches and parts lists should not mix work that must be done by different crafts.
- sketches should be prepared to show work exactly as workers will see it. For equipment, piping, or other products that will be installed on an assembly when it is upside down, the sketch should be drawn that way rather than for the final attitude plan view.
- a reference system should be used, and all dimensions should be from the reference system planes.
- information should be prepared so it can be issued on A4 sheets.

14.2.5.1 Structural workstation information

Today most shipyards use integrated CAD/CAM to prepare the lofting and to develop the necessary production aids for construction of the ship structure. This system eliminates the need for manual measuring and layout of plates. Therefore, the drawings used for subassembly, assembly, and module construction need not contain any dimensions other than check (accuracy control/dimensional tolererance) and quality assurance control dimensions. What is needed is a way to provide required information that is completely compatible with the way in which it will be used in various stages of construction of the structural hull and deckhouse.

This can be effectively and efficiently accomplished by using the following data packages:

For burning plate: Nest tape sketches and CNC information (Figure 14.6),

For cutting shapes: Process sheets, CNC information, and sketches (Figure 14.7),

For processing plate or shapes: Process sheets and templates,

For subassembly: Subassembly drawing and parts list,

For assembly: Assembly drawing and parts list,

For block construction: Block assembly sketches and parts list,

For on-block outfitting: Block outfitting sketches and parts list, and

For block erection: Hull block erection drawing and moving and lifting instructions.

Figures 14.8, and 14.9 show the workstation information packages for typical subassembly, and block, respectively. Note that for the assembly and module, the parts lists are separate from the drawings. The parts list should be sequenced in the way the product is to be constructed. Again, the product/phase chart can be used to develop the sequencing.

It is important to remember that all the information required by the workers to perform a work package should be included in the package. The worker should not have to obtain or look at any other drawing, work package, standard, etc., to complete the task.

14.2.5.2 Outfit workstation/zone information

The workstation/zone information will be provided for shops, assemblies, modules, and zones. The product/stage chart is helpful in deciding the work packages. Workstation information for shops for both processing and assembly will be required for hull fittings, pipe, sheet metal, foundation structure, joiner, paint, and electrical work. It is suggested that *zone* be used instead of the term *workstation* for all the logical breakdown of the total machinery space design and engineering, and the provision of workstation/zone information packages in place oftraditional working drawings. The machinery arrangement becomes a series of major pieces of machinery, units, and connecting system corridor/floor plate units. However, the quantity of information provided to production is vastly increased in scope compared to traditional engineering, plus all systems are given equal depth of consideration and are shown to the same detail. Figure 14.10 shows a typical work station/zone instruction sketch for outfit.

Workstation information for shops for both processing and

HULL NO. 75

NEST TAPE NT M 3 1 0 3

RUN NUMBER 1 REV. 0

STEEL BILL P13 PLT. SIZE 72 × 96

SCALE ½ = 1' BURN TIME HRS. ___ MIN. ___

NUMBER OF PLTS. NEEDED PER SHIP 4

LIKEWISE ONLY ☒ MIRROR IMAGE ONLY ☐

LIKEWISE AND MIRROR IMAGE NEEDED ☐

2 AXIS TAPE ☒ 3 AXIS TAPE ☐

WORKED BY ________ DATE ________

CHECKED BY ________ DATE ________

VALIDATED BY ________ DATE ________

APPROVED BY ________ DATE ________

PARTS NESTED

PART NO.	QTY	ASSY	PART NO.	ASSY
1	1	M35		
2	1			
3	8			
4	10			
5	2			
6	1			
7	1			
8	2			
9	2			
10	1			
11	1			
12	1			

REVISIONS

DESCRIPTION	WORK BY	DATE	CHKD BY	DATE	VALD BY	DATE	APRV BY	DATE

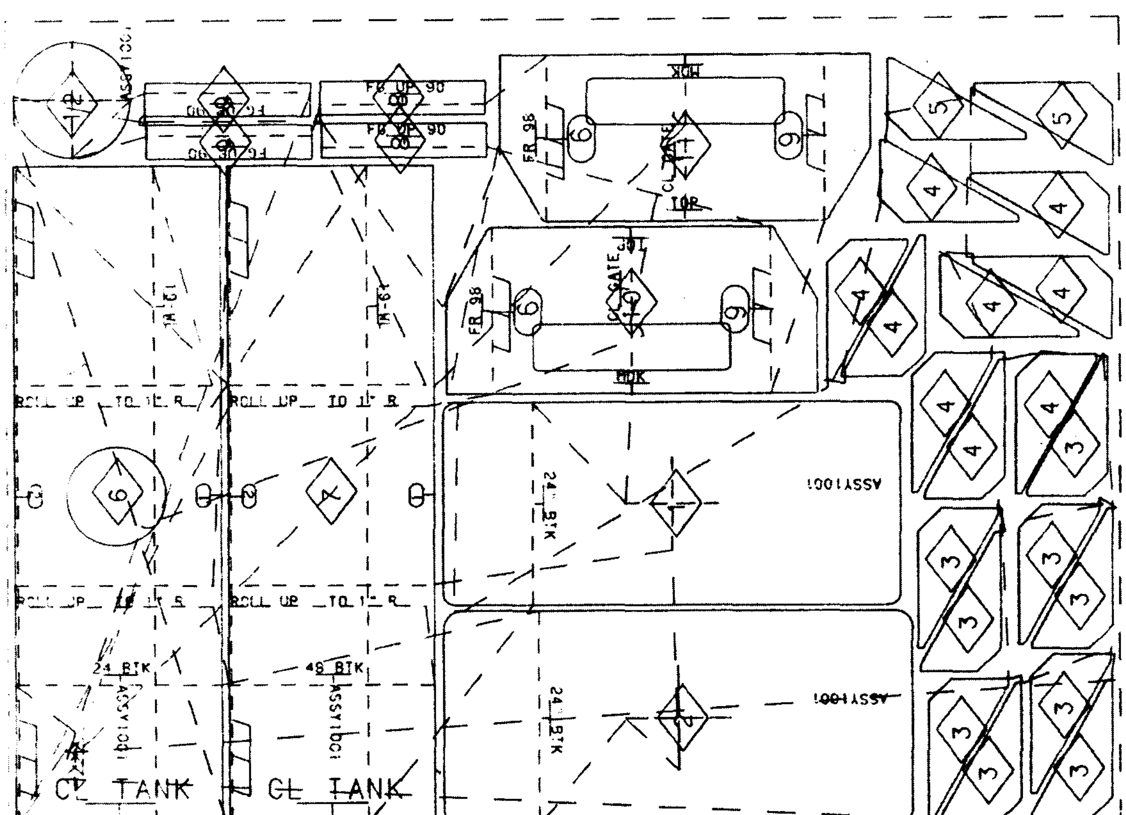


Figure 14.6 Structural Plate Process Sheet

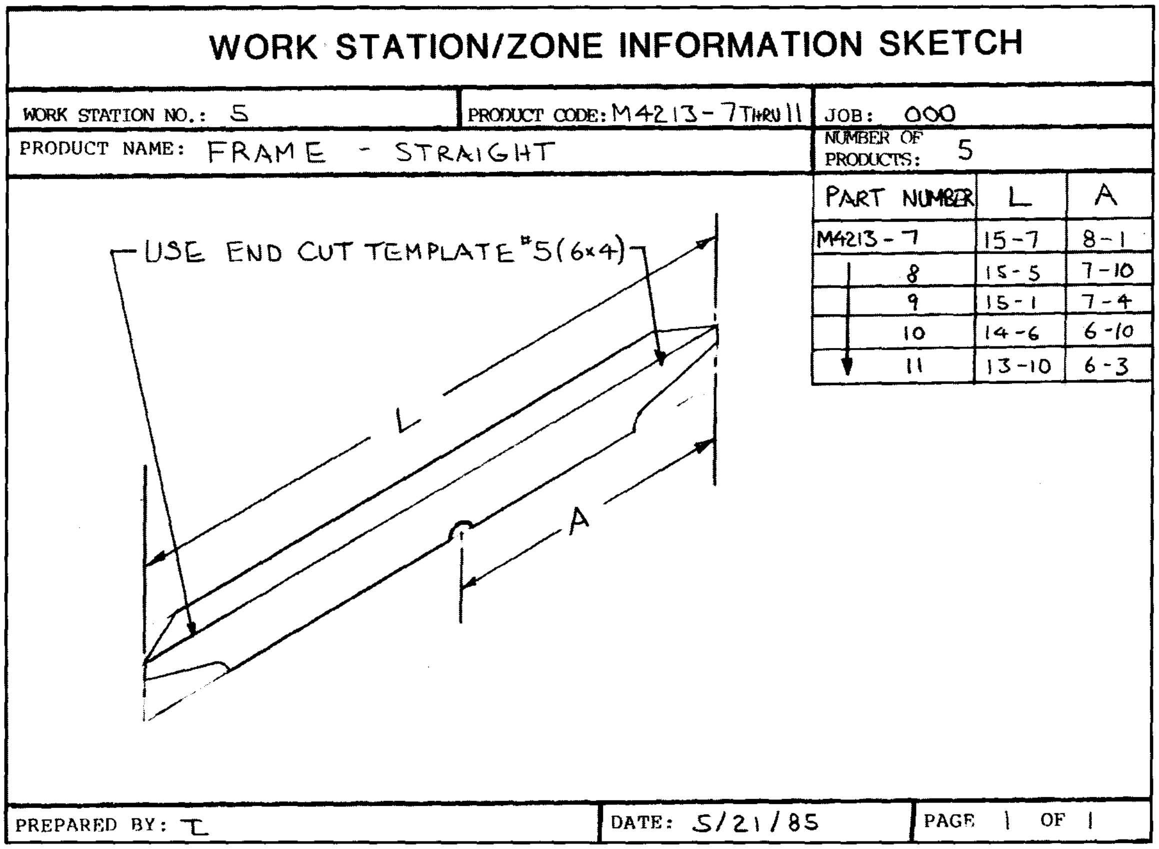


Figure 14.7 Structural Section Process Sheet

assembly will be required for foundation structure, pipe, sheet metal, paint, and electrical work. Workstation information will also be required for machinery installation, etc, for units.

Electrical fixtures in accommodation spaces should be located on the joiner work zone information sketches. All distribution panels, controllers, junction boxes, and other electrical equipment must be shown and located on installation sketches. The support connections to the structure should be included in the structural assembly and/or module workstation sketches.

14.2.5.3 Material requirements

Figure 14.11 summarizes the material definition approach for Engineering for Ship Production. It shows how the major equipment is defined by purchase technical specification during contract design. The majority of raw material is defined by advance material order per system during functional design.

During transitional design, all material remaining to be defined is identified. Also, through the product/stage chart approach (Figure 14.12), the preparation of the zone/unit lists is started. The sorting function, shown in Figure 14.11 under workstation/zone information, corresponds to the product/stage chart approach to work station parts list preparation.

A major requirement to ensure success of any material definition system is a detailed preparation and issue schedule compatible with the material ordering and material receipt requirements to construct the ship to plan. This integration of schedules must be a dynamic system, changing as circumstances change. It is not a once-prepared schedule that is followed even when it makes no sense.

14.3 DESIGN FOR PRODUCTION

It is possible to obtain significant increases in productivity in existing shipyards without large investments in plant by redefining the ship design approach and planning the ship construction at the same time the contract design is being prepared, thus being able to influence the design to suit the intended building approach.

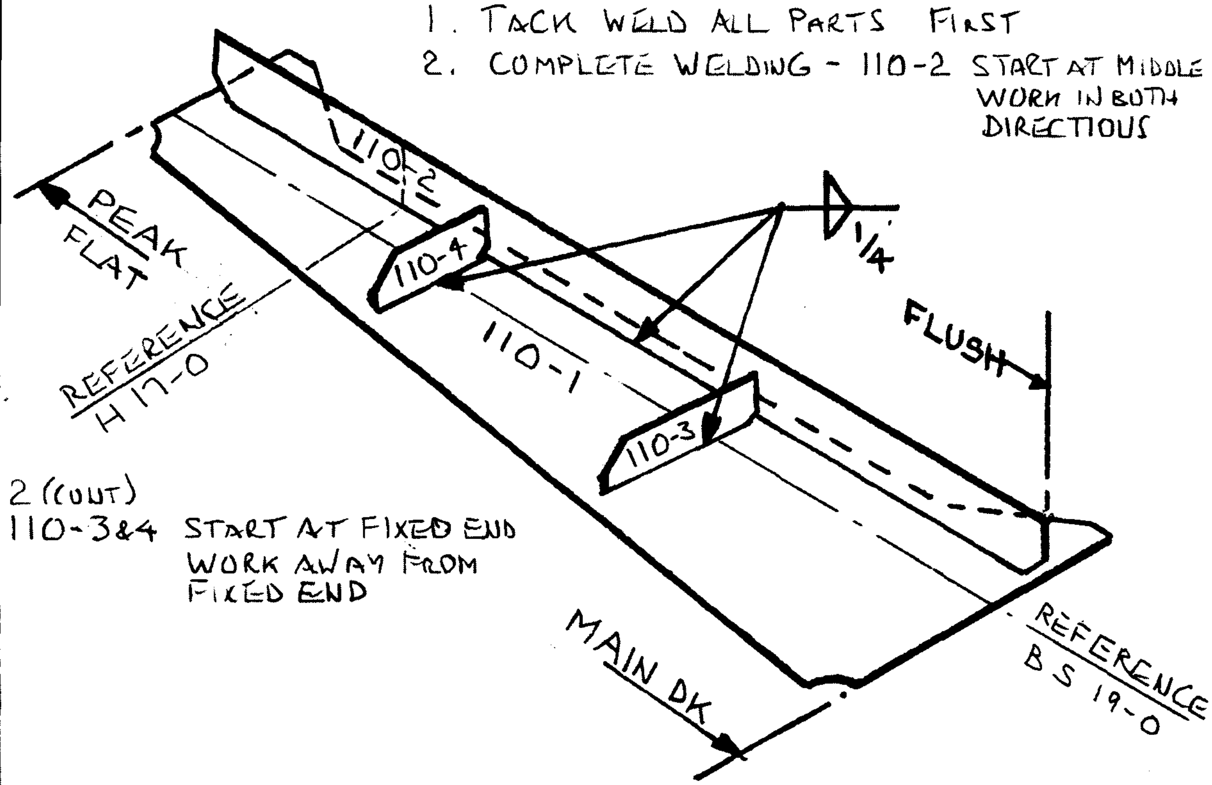
This demands that ship designers become more production conscious as they design future ships. Design for Production applied to shipbuilding is really Design for Minimum Cost of Ship Production through ease of production.

WORK STATION INFORMATION SHEET

WORK STATION NO.: S5	PRODUCT CODE: M 417	JOB: 000
PRODUCT NAME: SUB-ASSEMBLY		NUMBER OF PRODUCTS: 1 (ONE)

PART CODE	PART NUMBER	DESCRIPTION	QUANTITY PER PRODUCT	QUANTITY ALL PROD.
1000421600	110-1	0.375" PLATE	1	1
1100440200	110-2	6" x ½" FLAT BAR	1	1
1100130101	110-3	4" x ¼" FLAT BAR	1	1
1100130101	110-4	4" x ¼" FLAT BAR	1	1

1. TACK WELD ALL PARTS FIRST
2. COMPLETE WELDING - 110-2 START AT MIDDLE WORK IN BOTH DIRECTIONS



2 (CONT)
110-3&4 START AT FIXED END WORK AWAY FROM FIXED END

PREP. BY: T	DATE: 5-24-85	PAGE 4 OF 16

Figure 14.8 Structural Subassembly Workstation Information

WORK STATION/ZONE INFORMATION SKETCH

WORK STATION NO.: S 21	PRODUCT CODE: M 4	JOB: 000
PRODUCT NAME: MODULE - LOWER BOW		NUMBER OF PRODUCTS: 1

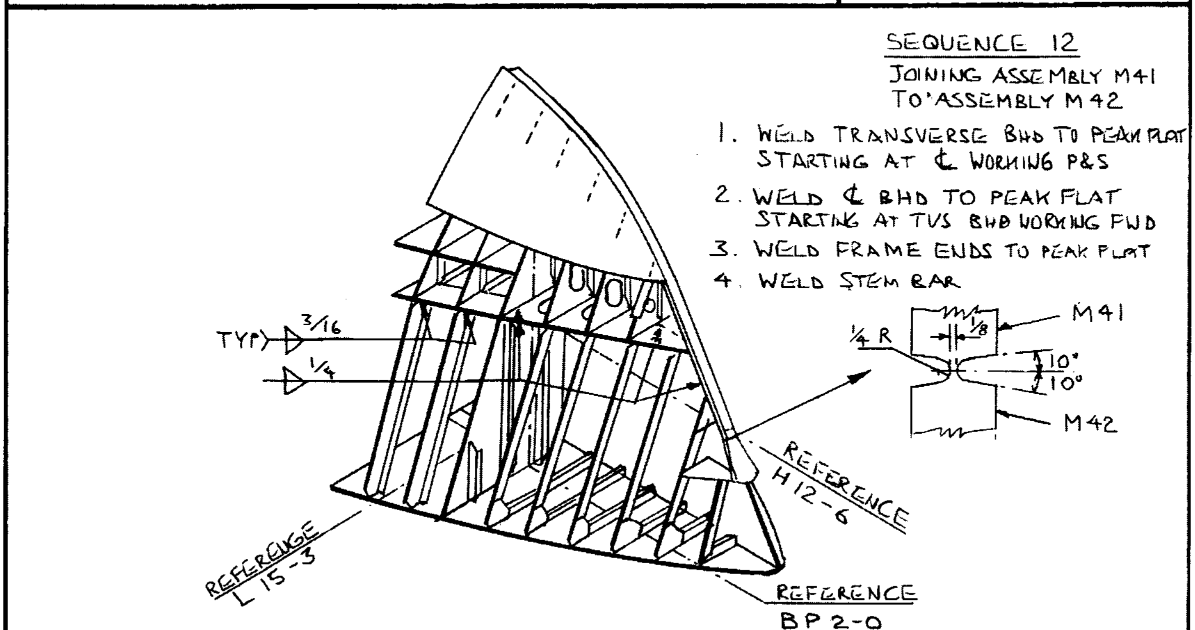


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Figure 14.9 Structural Block Workstation Iinformation

WORK STATION/ZONE INFORMATION SKETCH

WORK STATION NO.: 34	PRODUCT CODE: 321 - 300	JOB: 000
PRODUCT NAME: OUTFITTED UNIT - ELECTRIC		NUMBER OF PRODUCTS: 1 (ONE)

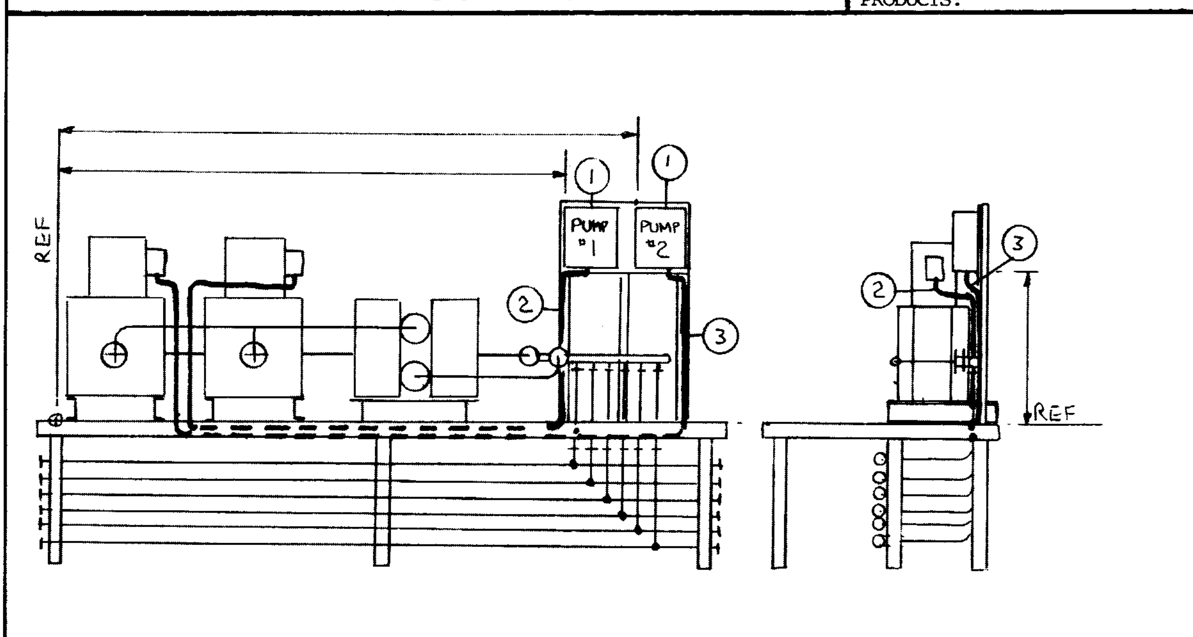

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Figure 14.10 *On-board* Advanced Outfitting Unit Installation Workstation Information

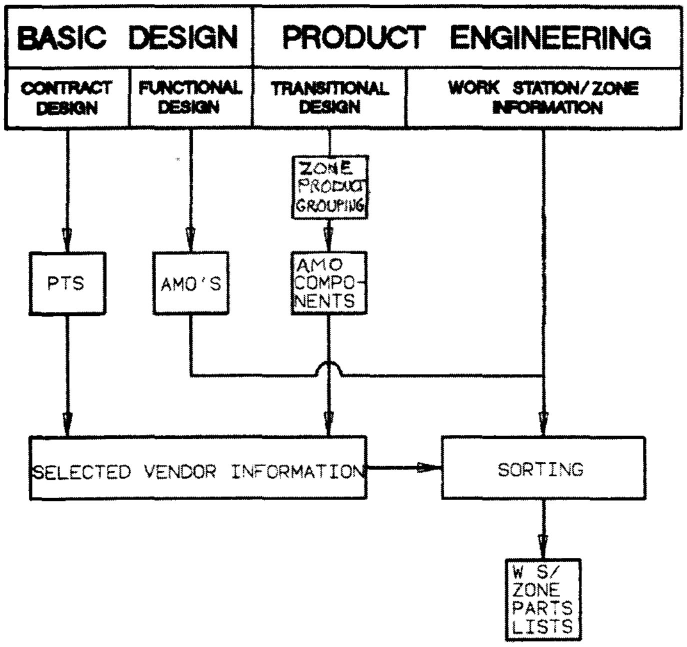


Figure 14.11 Material Definition Phases

This is accomplished by using the most efficient methods of construction while satisfying the many compromises resulting from the conflicting requirements between the shipowner, regulatory and classification rules, and the need to be competitive with other shipyards.

The need is obvious and it should not have been necessary to develop a new science (DFP) to achieve it. However, it seems that ship designers have not, in general, changed with the changes in ship production and satisfactorily responded to the new needs. Many ship design groups continue to work in isolation from shipyard production influence and do not take into account the producibility of their designs.

This is most unfortunate, as it is at this stage in the overall ship design and production process that the cost is being established and where there is the greatest opportunity to favorably, and vice versa, affect it. This is clearly seen from Figure 14.13, which shows that as the process moves from design into engineering, then planning and actual construction, the ability to influence cost, and therefore, achieve cost savings, diminishes. It is therefore essential that ship

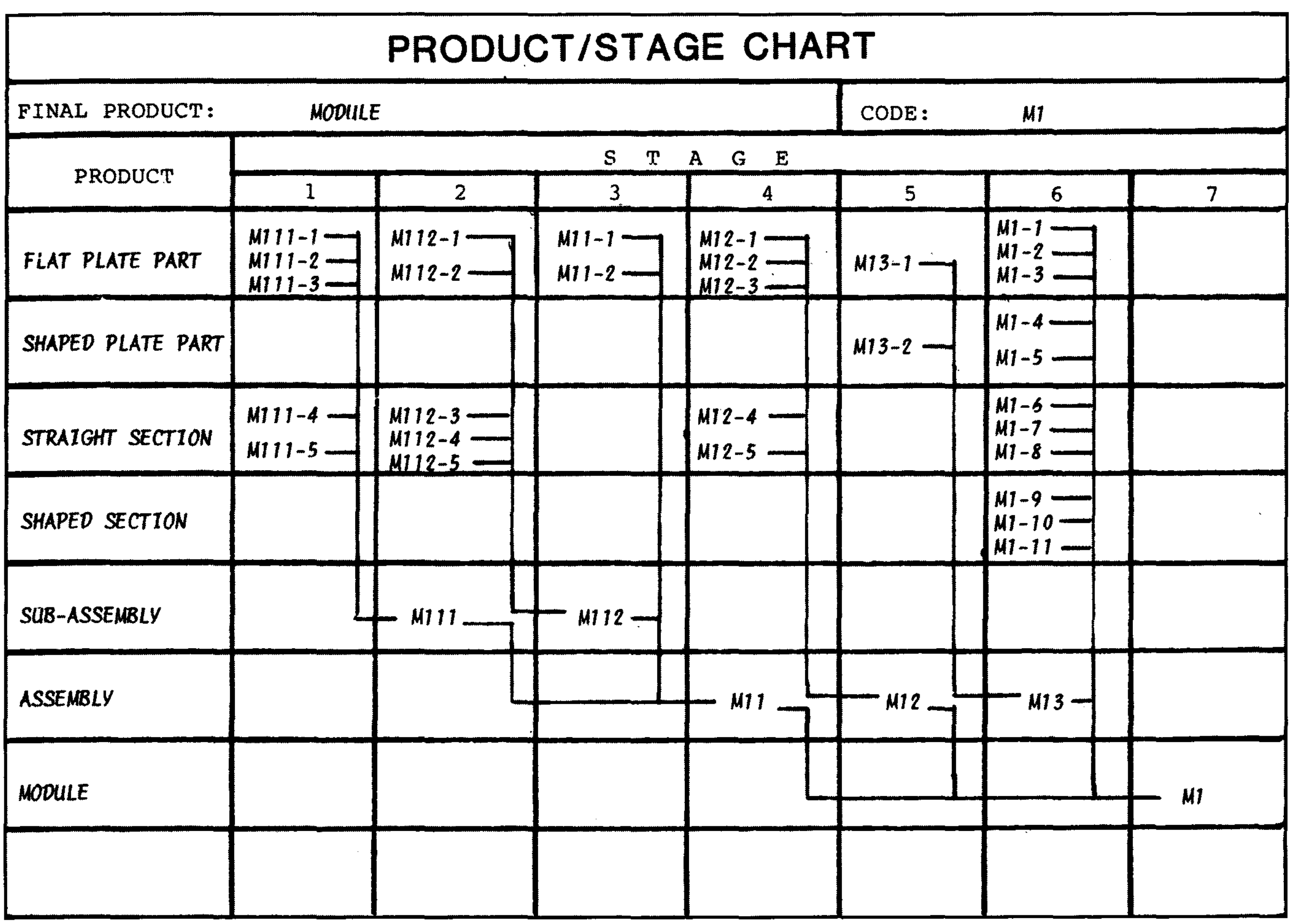


Figure 14.12 Product/Stage Chart

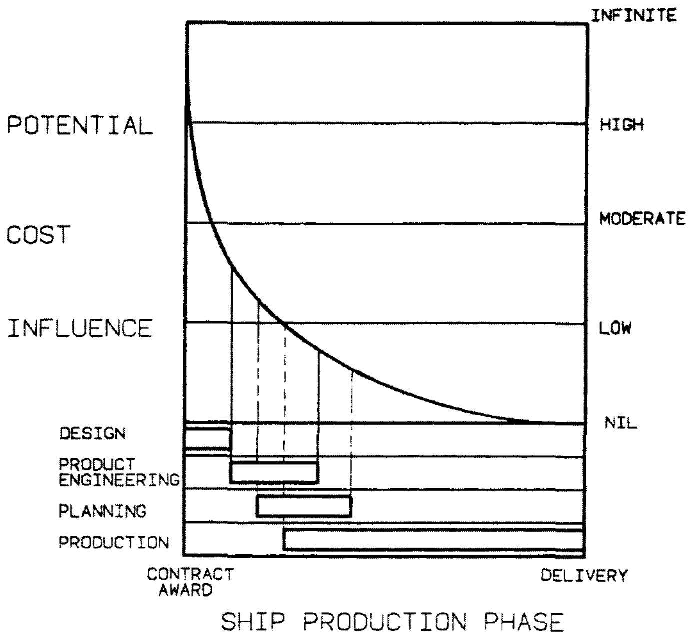


Figure 14.13 Potential Cost Influence as Design and Build Phase Progresses

design agents develop a way to correct the current lack of production considerations in their designs for all future contracts in which they are involved. At the start of any contract design they should find out from the customer the shipyards that will be invited to bid for the contract, and spend time with the planning and production staffs of these shipyards to develop an understanding of their facilities, planning and preferred construction approaches and any standards developed by the shipyards.

To accomplish this, the ship designer must become better educated in ship production processes and their relative costs.

More recently, Design for Production has been defined as the deliberate act of designing a product to meet its specified technical and operational requirements and quality so that the production costs will be minimal through low work content and ease of fabrication and assembly.

Design for Production is not:

- improvements in facilities,
- improvements in materials, and
- alterantive shipboard equipment;

UNLESS

- DFP was the major driver in bringing about the change.

It is simply addressing the fact that today's ship designers have a commitment to assess their ship designs for high productivity. To do this, they must consider the relative efficiencies of available production processes and construction methods. This places additional responsibility on the designer. However, it must be willingly accepted, because if it is not, the effect on production costs can be fatal to a shipyard. Today's ship designer has both the opportunity and the obligation to design production-friendly ships. The'Ship designer in isolation cannot seize this opportunity. It is only possible through an awareness of the shipyard facilities and methods used in the shipyard that will build the design. This necessitates continual interface and cooperation between the engineering, planning, and production departments.

The principal problem for Design for Production is the development of this knowledge for the ship designers. This can be accomplished by the development of *Shipbuilding Policy* for each shipyard and *Build Strategy* for each ship to be built (see section 14.4). Ship designers constantly refer to the ship's *Contract Specifications* for the technical and quality requirements of the ship. It is suggested that they should likewise refer constantly to the Shipbuilding Policy and the Build Strategy for how the ship is to be constructed and to design accordingly. More details on both can be found in (15). While the Contract Design is progressing, the Build Strategy would be developed in parallel. The completion of the design during the Functional Design phase must obviously be in accordance with the Build Strategy.

Two recent papers (16,17), by the same authors, on Ship Structural Design for Production, state that its application is ineffective without a meaningful merit factor and that such a factor must be based on a production costing technique capable of taking into account different physical design differences as well as production processes. While much can be gained from the intuitive approach by knowledgeable and experienced designers, with and without input from planning and production, it is still subject to differences of opinion, and the danger of errors of omission. That is, some aspect, process or work task can be left out of the consideration. It would obviously be better to use an industry, or at least, a company, accepted Merit Factor for the basis of the analysis. Unfortunately, there is no merit factor currently available, and it is only necessary to try to discuss this matter with an experienced ship construction estimator to appreciate the extent of this problem.

Most Ship Cost Estimating systems do not consider the design or construction tasks in sufficient detail to be able to be used as a Design for Ship Production Merit Factor. For example, for structure the cost estimating system may use combinations of total ship or block steel weight, complexity factors, average weight per unit area and joint weld length. These are not enough for a merit factor that will allow changes in detail to be compared. What is required is a method that takes into account all the design and production factors that can differ. At the present time such a method does not exist, nor is there an existing historical data library from which it could be developed. It is necessary, therefore, to develop an approach, and then collect the data required to use the approach. This is where the application of Work Measurement and Method Study techniques can help.

From the previous description, it should be obvious that what is proposed is not a simple exercise. Significant effort would be involved as well as the potential to interrupt normal work in a shipyard. Nevertheless, it is necessary that the approach be completely developed if full benefits are to be obtained from the use of Design for Ship Production.

This has been attempted by 1. Wolfram (18), for welding man-hours in a shipyard panel shop. The resulting equation is

$$\text{Welding Man-hours} = 2.79 \times NPS + 0.0215 \times JLFB \times t_{FB} + 0.097 \times JLCB \times t_{CB} + 0.017 \times JLF \times FCSA$$

where

NPS = number of panel starts
JLFB = joint weld length of flat panel butts
t_{FB} = thickness of flat panels
JLCB = joint weld length of curved panel butts
t_{CB} = thickness of curved panels
JLF = joint weld length for fillet welds
FCSA = cross-sectional area for fillet welds

The same approach could be used for all other shipbuilding processes with the final system becoming an effective labor estimating tool for both new construction cost estimating and trade-off analysis. Until such an approach is fully developed for all processes, a less precise but similar approach could be used by applying known data and *guesstimates* to the various design and production factors for each design alternative. Figure 14.14 shows a form that can be used to perform a manual calculation for work content and cost for a structural part.

Similar forms would be used for sections, subassemblies, assemblies, blocks and the erection and joining of the blocks. Obviously, the calculation could be programmed and run on a computer, and it is even feasible to link the computer program with an interactive computer graphics system, which would present the desired merit factor for each design detail, as it was developed. Similar forms, or programs, could be developed for all other ship systems and production processes.

Design for Ship Production can, therefore, be applied in a number of ways, varying from a simple ease of fabrication *gut feeling* decision to a very detailed analysis using work measurement and method study techniques. The latter are considered the domain of Industrial Engineering, but a good understanding of them will improve the ship designer's ability to prepare the best production oriented designs for a given shipyard.

Most ship designers will not have either the experience or the time to use such techniques in their normal design decision process. However, if an Industrial Engineering capability exists in their shipyard, they should take every opportunity to benefit from it. If possible, they should work with the Industrial Engineers to arrive at the best design for their shipyard. If such a capability does not exist in the shipyard or it is too busy with the many other areas they are involved in, and it is not reoriented by management, Design for Ship Production can still be performed. The ship designer with a team from planning and production can develop the different ways to design a detail and rank it on the basis of producibilty and cost aspects.

When complete, the selected *best* design and the selection analysis can be sent to the other departments that are involved in the process, for their review and concurrence. It is strongly recommended that a Design for Ship Production team be established to review and maintain a shipyard's existing standards, and at an early stage of all new ship design development to ensure that the design will be the most producible and cost-effective design for their shipyard. Table 14.1 is suggested as a minimum procedure for applying Design for Ship Production based on experience and intuition of such a team.

In some shipyards, the only design that is performed inhouse, is the *Production Design*, such as working drawings for the shipyard and any calculations necessary to prepare them, which will be based on an owner provided Contract Design and Specifications.

The subject of ship design is well covered in many books and in the transactions of the naval architecture and marine engineering professional societies. It will be discussed only to the extent necessary for the incorporation of Design for Ship Production.

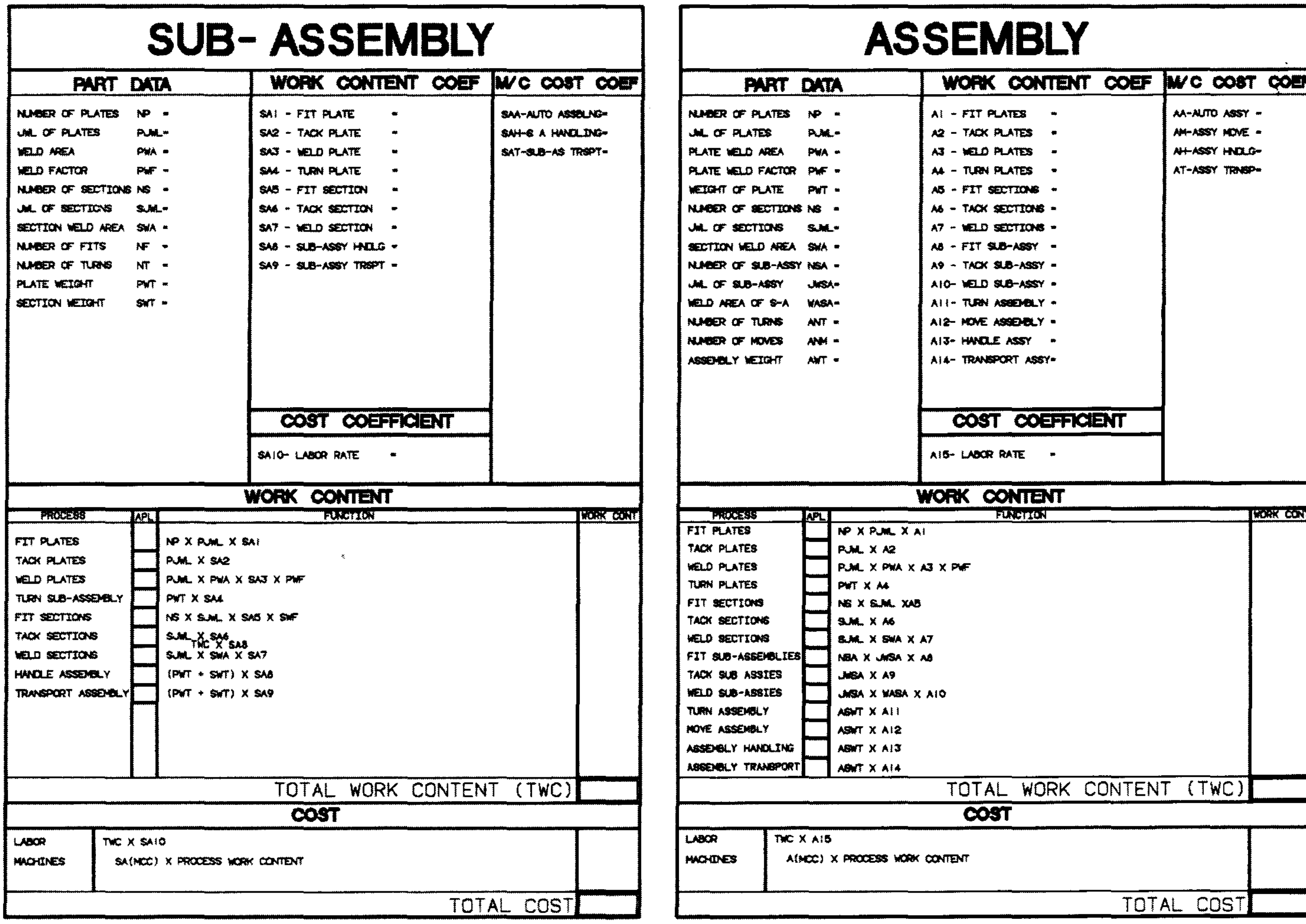
14.3.1 OFP Principles

There are two main principles for DFP for ships, namely

1. all design should strive for simplicity, and
2. all design should be the best suitable for a given shipyard facility.

These can be further expanded as follows:

Simplicity in Design
- minimum number of parts,
- minimum number of parts to be formed,
- reduction of part variability,
- reduction in joint weld length,
- part standardization,
- minimum fitting/fairing of erection joints,



SUB-ASSEMBLY

PART DATA

NUMBER OF PLATES NP =
JWL OF PLATES PJWL=
WELD AREA PWA =
WELD FACTOR PWF =
NUMBER OF SECTIONS NS =
JWL OF SECTIONS SJWL=
SECTION WELD AREA SWA =
NUMBER OF FITS NF =
NUMBER OF TURNS NT =
PLATE WEIGHT PWT =
SECTION WEIGHT SWT =

WORK CONTENT COEF

SA1 - FIT PLATE =
SA2 - TACK PLATE =
SA3 - WELD PLATE =
SA4 - TURN PLATE =
SA5 - FIT SECTION =
SA6 - TACK SECTION =
SA7 - WELD SECTION =
SA8 - SUB-ASSY HNDLG =
SA9 - SUB-ASSY TRSPT =

COST COEFFICIENT

SA10- LABOR RATE =

M/C COST COEF

SAA-AUTO ASSBLNG=
SAH-S A HANDLING=
SAT-SUB-AS TRSPT=

WORK CONTENT

PROCESS	APL	FUNCTION	WORK CONT
FIT PLATES		NP X PJWL X SA1	
TACK PLATES		PJWL X SA2	
WELD PLATES		PJWL X PWA X SA3 X PWF	
TURN SUB-ASSEMBLY		PWT X SA4	
FIT SECTIONS		NS X SJWL X SA5 X SWF	
TACK SECTIONS		SJWL X SA6 TWC X SA8	
WELD SECTIONS		SJWL X SWA X SA7	
HANDLE ASSEMBLY		(PWT + SWT) X SA8	
TRANSPORT ASSEMBLY		(PWT + SWT) X SA9	
		TOTAL WORK CONTENT (TWC)	

COST

LABOR	TWC X SA10	
MACHINES	SA(MCC) X PROCESS WORK CONTENT	
	TOTAL COST	

ASSEMBLY

PART DATA

NUMBER OF PLATES NP =
JWL OF PLATES PJWL=
PLATE WELD AREA PWA =
PLATE WELD FACTOR PWF =
WEIGHT OF PLATE PWT =
NUMBER OF SECTIONS NS =
JWL OF SECTIONS SJWL=
SECTION WELD AREA SWA =
NUMBER OF SUB-ASSY NSA =
JWL OF SUB-ASSY JWSA=
WELD AREA OF S-A WASA=
NUMBER OF TURNS ANT =
NUMBER OF MOVES ANM =
ASSEMBLY WEIGHT AWT =

WORK CONTENT COEF

A1 - FIT PLATES =
A2 - TACK PLATES =
A3 - WELD PLATES =
A4 - TURN PLATES =
A5 - FIT SECTIONS =
A6 - TACK SECTIONS =
A7 - WELD SECTIONS =
A8 - FIT SUB-ASSY =
A9 - TACK SUB-ASSY =
A10- WELD SUB-ASSY =
A11- TURN ASSEMBLY =
A12- MOVE ASSEMBLY =
A13- HANDLE ASSY =
A14- TRANSPORT ASSY=

COST COEFFICIENT

A15- LABOR RATE =

M/C COST COEF

AA-AUTO ASSY =
AM-ASSY MOVE =
AH-ASSY HNDLG=
AT-ASSY TRNSP=

WORK CONTENT

PROCESS	APL	FUNCTION	WORK CONT
FIT PLATES		NP X PJWL X A1	
TACK PLATES		PJWL X A2	
WELD PLATES		PJWL X PWA X A3 X PWF	
TURN PLATES		PWT X A4	
FIT SECTIONS		NS X SJWL XA5	
TACK SECTIONS		SJWL X A6	
WELD SECTIONS		SJWL X SWA X A7	
FIT SUB-ASSEMBLIES		NSA X JWSA X A8	
TACK SUB ASSIES		JWSA X A9	
WELD SUB-ASSIES		JWSA X WASA X A10	
TURN ASSEMBLY		ASWT X A11	
MOVE ASSEMBLY		ASWT X A12	
ASSEMBLY HANDLING		ASWT X A13	
ASSEMBLY TRANSPORT		ASWT X A14	
		TOTAL WORK CONTENT (TWC)	

COST

LABOR	TWC X A15	
MACHINES	A(MCC) X PROCESS WORK CONTENT	
	TOTAL COST	

Figure 14.14 Structural Work Content and Cost Calculation Form

- elimination of need for highly accurate fitting,
- integration of structure and outfit,
- elimination of need for staging, and
- consideration of access.

Matching to Shipyard Facilities

- checking that blocks and machinery package units and outfitted blocks are within shipyard lifting capability,
- assembly and block sizes fit panel line, workstations and door openings,
- use maximum plate sizes and corresponding block breaks to minimize connecting joint weld length, and
- maximize design for in-shop versus on-ship work.

14.3.2 Tailoring Design to Facilities

While it is beneficial for a shipyard to be able to build any ship design, it is a well known fact that such general capability will increase the cost to build the shipowner's custom design than one which is designed to make best use of a shipyard's facilities. Obvious shipyard imposed requirements are:

- ship dimensions and limits,
- block maximum weight,
- block maximum size,
- panel maximum size, and
- panel line turning and rotating capabilities.

Obviously, a shipyard would be unwise to attempt to build a ship which was longer or wider than the building berths and/or docks, or higher than the cranes could reach. Of course, this would not be so if part of the building plan was to improve the facilities.

The block maximum weight can be dictated by berth or shop crane capacity, and/or transporter capacity; also, by advanced outfitting and any temporary bracing and lifting gear used for the lift. The block maximum size will depend on access throughout the shipyard for the blocks from as-

TABLE 14.1 Application of Design for Ship Production

1. Examine Existing Design
   a) count the number of unique parts
   b) count the total number of parts
   c) count number, type and position of joints
   d) evaluate complexity of design
      - simple measurement
      - simple manual layout
      - complicated manual layout
      - CAD/CAM applicability
      - required manual processing
      - required machine processing
   e) Producibility aspects
      - self-aligning and supporting
      - need for jigs and fixtures
      - work position
      - Number of turns and moves
      - Aids in dimensional control
      - Space access and staging
      - Standardization
      - number of compartments entered to complete work
2. Examine Alternative Design(s) in same manner
3. Select the Design that meets the objective of Design for Production, which is: *The reduction of production cost to the minimum possible through minimum work content and ease offabrication, while meeting the design peiformance and quality requirements.*

sembly to erection, shop door sizes and the shipyard's maximum plate size. The panel maximum size will depend on panel line limits as well as any access limits. It will also be impacted by whether the panels need to be turned and/or rotated. A panel line with no rotation capability can achieve the same results by vertical plate straking of shell and bulkheads when the ship is transversely framed and the bulkheads vertically stiffened.

Not so obvious and often ignored requirements are:

- maximum berth loading,
- spread of launch ways, and
- maximum launch pressure on the hull.

The maximum berth loading could affect the extent of outfitting before launch and thus the productivity achieved in building the ship. Heavy concentrated weights, such as propulsion engines and gears, and independent LNG tanks may not be able to be installed until the ship is afloat. The spread of the launchways should be matched by basic ship's structure, such as longitudinal girders, in order to eliminate the need for any additional temporary strengthening, which only adds to the work content. Likewise, the structure of the ship in way of the area subjected to maximum way end pressure and the fore poppet should be designed to withstand these loads without the need for additional temporary structure.

Whatever the facility requirements on the design, it is obvious that they must be fully industrial engineered, well documented and communicated to the designers. The use of computer simulation techniques (19) can serve as both an educational and informational tool to give ship designers a better understanding of the capabilities of a shipyard. The already stated concept of Shipyard Specifications of parallel importance and applicability as the usual Contract Ship Specifications would also be an effective way to accomplish the transmission of the information to the ship designers. However, it would not in itself assure production-oriented designs. To assure this, it is essential that the ship designers be educated and trained in the field of Design for Ship Production.

14.3.3 Design for Production in Basic Design

Basic Design covers all design from Conceptual through to at least Contract Design, that is *concept, preliminary,* and *contract design.* It is proposed that it should also cover *Functional Design.* Functional design is the phase where the contract design is expanded to encompass all design calculations, drawings, and decisions, thus defining all systems and required material.

Design for Production must be applied during basic design. The structural breakdown definition as well as zone and advanced outfitting *On-umit, On-block,* and *On-board* definitions must be decided during this phase.

The other phase of design, conducted after contract award, is usually called Detailed Design. It usually covers all remaining activities to document the design. It usually does not incorporate production considerations. The author uses the term Product Engineering to differentiate between the traditional Detailed Design and production-oriented documentation.

Product Engineering covers all tasks required to prepare the technical information to be transmitted to production and other shipyard groups to assist and direct the construction of the ship. It is divided into two phases. The first, transitional design is the task of integrating all design information into complete zone design arrangements and to complete the ordering/assigning of all materials. The second, work station/zone information preparation, is the task of providing all drawings, sketches, parts lists, process instructions and production aids (such as numerical control [N/C] tape for plate burning/marking and pipe fabrication) required by production and other service departments to construct the ship.

Figures 14.15 and 14.16 show the relationship of Basic and Production Design and the lower classes such as Concept Design, Preliminary Design, etc.

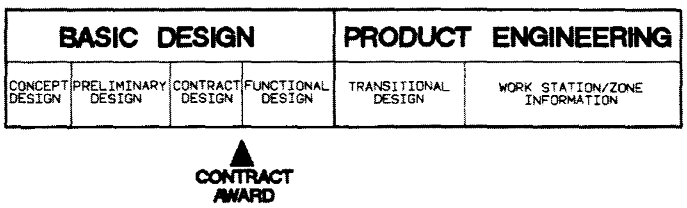


Figure 14.15 Design Stages

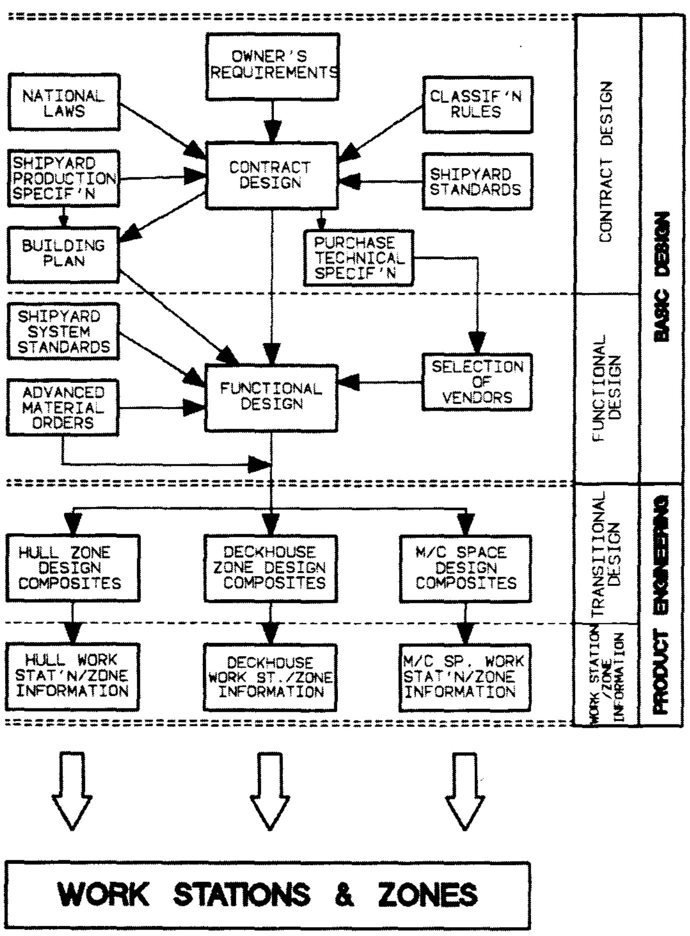


Figure 14.16 Design Flow

Throughout basic design, the tasks are accomplished on a system basis, whereas throughout product engineering, ,the tasks are accomplished on a zone basis for transitional-design and a work station/zone basis for work station/zone information.

14.3.3.1 Hull form design

A Lines Drawing developed without consideration of the impact on production of its various work content aspects can increase the work content significantly, and prevent the achievement of high productivity and lowest construction cost. Double and reverse curvature surfaces, *clipper bows, cruiser stems,* keel, stem and stern half sidings, and inappropriately located *knuckleslchines* all add work content.

The development of low resistance and efficient propulsion lines is a highly specialized field and often is performed by naval architects and hydrodynamicists with very little shipyard engineering and production experience. While it is not proposed that consideration of the producibility aspects be allowed to overrule the lines designer's decision where it could adversely affect the efficient operation of the ship after it is delivered, it is proposed that lines designers should obtain a better understanding of the impact their design decisions have on the producibility of the ship. They should then incorporate producibility improvement aspects that have a high work content reduction and a small, if any, adverse impact on hydrodynamic and propulsion efficiency. In this context, it should be remembered that a seagoing ship hardly ever operates in smooth water, and that the impact of any producibility change should be considered in its seagoing environment, and not the result of a smooth water model towing tank test.

Ship hull form design has to consider hydrodynamic and producibility aspects and find a acceptable compromise. Hydrodynamic aspects, especially minimization of power requirements, lead to rather streamlined hull shapes that are relatively expensive to produce. Producibility aspects depend on the production process and the material used. It is therefore important to understand at least the most important implications of production techniques and materials for design. Changing technologies and materials lead to different *optimum* results.

Prior to the mid-19th century most ships were made of wood. Wood limited the size of the ships, but the limiting fairing properties of the material resulted in automatically *fair* ship hulls with usually good hydrodynamic properties. Wooden hulls featured rather smooth curvature. Basically the same principles for hull form design were applied to the first steel ships. Even full hull forms were still designed without flat bottom or sides even in the early 20th century. Ship designers only gradually realized that hull design had to take into account producibility aspects, and these in turn changed with materials (from wood to steel) and production processes (from riveting to welding). But eventually ship designers realized that steel hulls for full hull forms, that is tanker and bulk carrier, could be designed with large parallel midbodies with rather rectangular cross sections without seriously decreasing the hydrodynamic properties of the ship.

New materials such as fiber-reinforced plastics, and new production technologies such as laser welding or adhesive bonding may yet lead to another change in *best* hull forms, but only aspects of producibility for welded steel hulls using shipyard technology widely available today (2003) will be considered in this chapter. Nevertheless, the example of material technology shift from wooden to steel ships impact on hull form should teach us that producibility in design is not a static process, but rather that general principles change as technology and material change.

The *optimum* hull will always be a trade-off of production cost and operation cost subject to various constraints. Production cost depend on available production technology and labor cost. Operation cost depend on fuel prices. In addition, constraints such as delivery times may yet introduce another factor shifting the optimum hull. For example, in times of war it was necessary to produce transport capacity in a very short time favoring hull forms that are easy to produce, while having rather high fuel consumption. Thus the naval architect will always have to find an appropriate trade-off and no general rule for all times can be given.

The construction of steel ships involves a large number of steel plates, which form the hull surface panels. These plates and shapes require usually special shaping, unless they are in a region of the ship where the hull is flat, such as in parts of the bottom or side plating in the parallel midbody of the hull.

In modern shipbuilding, there are two main processes in plate forming and stiffener forming:

1. *Cold forming* involves using rolls and presses to shape plates and stiffeners, and
2. *Thermal forming* involves line heating using torches and lasers.

Plates that need to be shaped in only one direction (single curvature) or with only a slight amount of backset can be formed using rolls. These large machines typically consist of a large diameter top roll and two small diameter bottom rolls.

Plates with complex (reverse) curvature or large curvature in both directions (double curvature) are fabricated using large hydraulic presses. Depending on the shipyard fabrication facilities, the types of presses used and the ways in which they are used may vary. A standard line press may be used for moderate double curvature and a ring press may be used for severe double and reverse curvature.

In the forming of many curved plates, the required shape exceeds the capacity of cold forming techniques. In these cases, heating the plates in a furnace to make them more malleable may be required. Thermal forming (line heating) techniques can be used alone or in conjunction with cold forming to produce the desired curvature while keeping residual stresses in the material at an acceptable level. Line heating is the process of heating, by a narrow heat source such as an oxygen flame torch, and cooling the upper surface, by a stream of water, a plate in a series of lines to produce a the desired shape. Procedures for line heating depend on material type and size. Line heating is often used to finish a plate to the desired shape. Line heating is a very labor intensive and high skill process. Computer controlled line heating machines have been developed by some Japanese shipyards reduce the work, and full automation appears possible for the future (20).

Even in full form hulls the work content in forming the curved shell plates and fitting them to the internal structure is a significant portion of the total structural man-hours. This is because of the high manual and skill level required to form the plates to their required shape. Because it is a manual process requiring high skill, it is not a repeatable process and suffers from inaccuracy. That this is recognized as a major problem can be seen from the efforts over the years to eliminate/reduce the extent of curved shell plates. Therefore, when preparing a lines drawing, the following items must be considered from a producibility point of view.

Historical review of simplified hull forms Producibility in design of the hull form of steel ships is not a new concept. Among the historical attempts in this direction are:

- William McEntee (21) presented a paper on probably the first major work directed specifically towards simplifying hull forms stimulated by the need during World War I to produce quickly, more transport capacity. In his work, McEntee tested three sets of models representing both conventional and simplified hull forms for a barge, a cargo ship, and a collier. The degree of simplification consisted of using vertical wall-sided sections over the entire length, straight bottom sections with no deadrise forward, a plumb bow, and the bottom and sides joined by circular arcs McEntee concluded, based on the results of his model tests, that simplified hull forms could be designed with calm-water resistance about the same as conventional forms. (The general validity of this conclusion especially for modern hull forms has to be doubted.)

- A year later, Sadler (22) gave a comprehensive report of his investigations concerning the resistance penalty entailed by simplifying hull forms. The forms examined were even simpler than those of McEntee. Even with such very elementary forms, Sadler concluded that vessels with straight frames may have the same resistance as faired shapes.
- Similar work in Great Britain resulted in the construction of the *N* (National) type standard ship during World War I (23). The British investigations basically supported the conclusions reached by McEntee and Sadler. As the wartime crisis abated, the interest in simplifying hull forms also subsided. However, the discussion about various ideas did not stop completely (24, 25).
- In 1919, ship made of concrete were built due to the shortage of steel. The material and production technology required rather simple hull forms which would see a renaissance in World War II.
- In a survey paper, John McGovern (24) discussed the emerging technology of fully welded ships and its implications on ship hull forms. He proposed a simplified hull form. All frames were straight except for the circular bilge and part of the forecastle. McGovern found again that the simplified form had only marginal hydrodynamic disadvantages compared to a fully faired hull form: *Two series of models were tested in the experimental tank. The selected model was such that the speed and resistance qualities of this form were shown to be equivalent to models of the best ordinary form having the same dimensions and displacement.*
- World War II again saw renewed activity in the area of simplified hull forms. Although most construction of

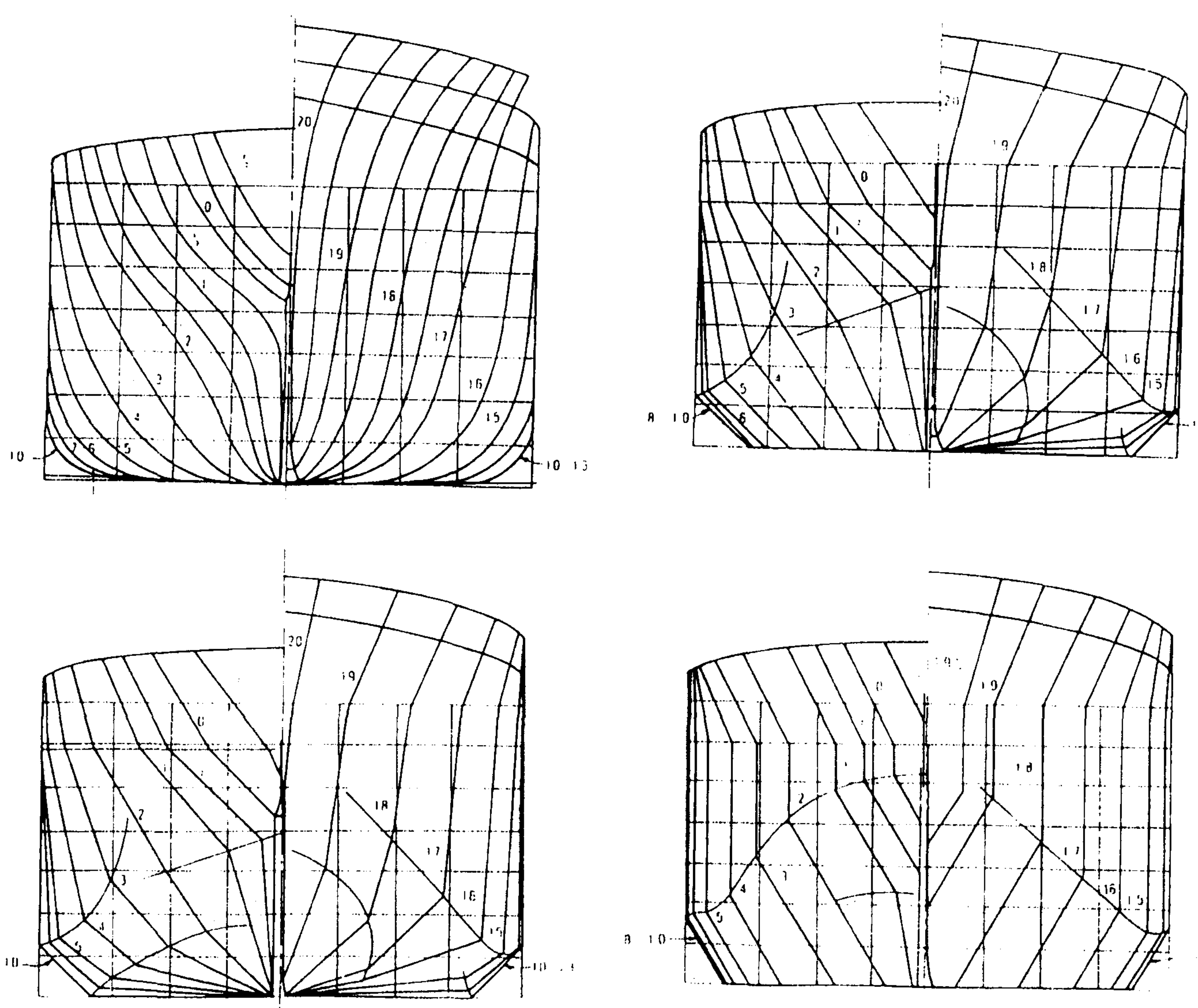


Figure 14.17 Body Plans of Johnson's (1964) "71" Series (26)

simplified hulls involved small craft and auxiliaries, the U.S. Maritime Commission had 24 CI-S-Dl concrete steamers constructed in 1943-1944, Post-war interest subsided again, especially for oceangoing ships.

- Johnson (26) conducted extensive series of model tests to investigate the resistance and propulsion of simplified hull forms in calm water. Johnson noted that chines or knuckle lines should be aligned along streamlines to avoid high drag due to vortex shedding. To accomplish this, he began with a ship of conventional form, found the streamlines, and then designed a ship with straight frames with general character close to the conventional form. He investigated a series of successively simplified hull forms (Figure 14.17). Two series were investigated, one with block coefficient 0.71, one with block coefficient 0.82. For the fuller hull, the power requirements increased by at least 16%. However, for the hull with block coefficient 0.71, the moderate simplification of the *B* version had 4.7% power reduction at design speed and draft! (The extreme simplified form D had a 39.8% increase in power requirement.) At non-design draft and trim the performance was not superior, but still comparable to that of the original round form.
- The *Pioneer* hull form developed and patented by Blohm & Voss in Hamburg featured only flat plates on the hull except for the regions on the ship ends, Figure 14.18 (27-29). This introduced a multitude of knuckles. Contrary to the expectation of the designers, this resulted in a more difficult assembly process due to fitting problems. Fatigue strength problems appeared after some years of operation in these ships. In addition, Kiss (30) concluded, based on his analysis, that the savings in hull construction would not be able to offset the cost for fuel and power plant increases.

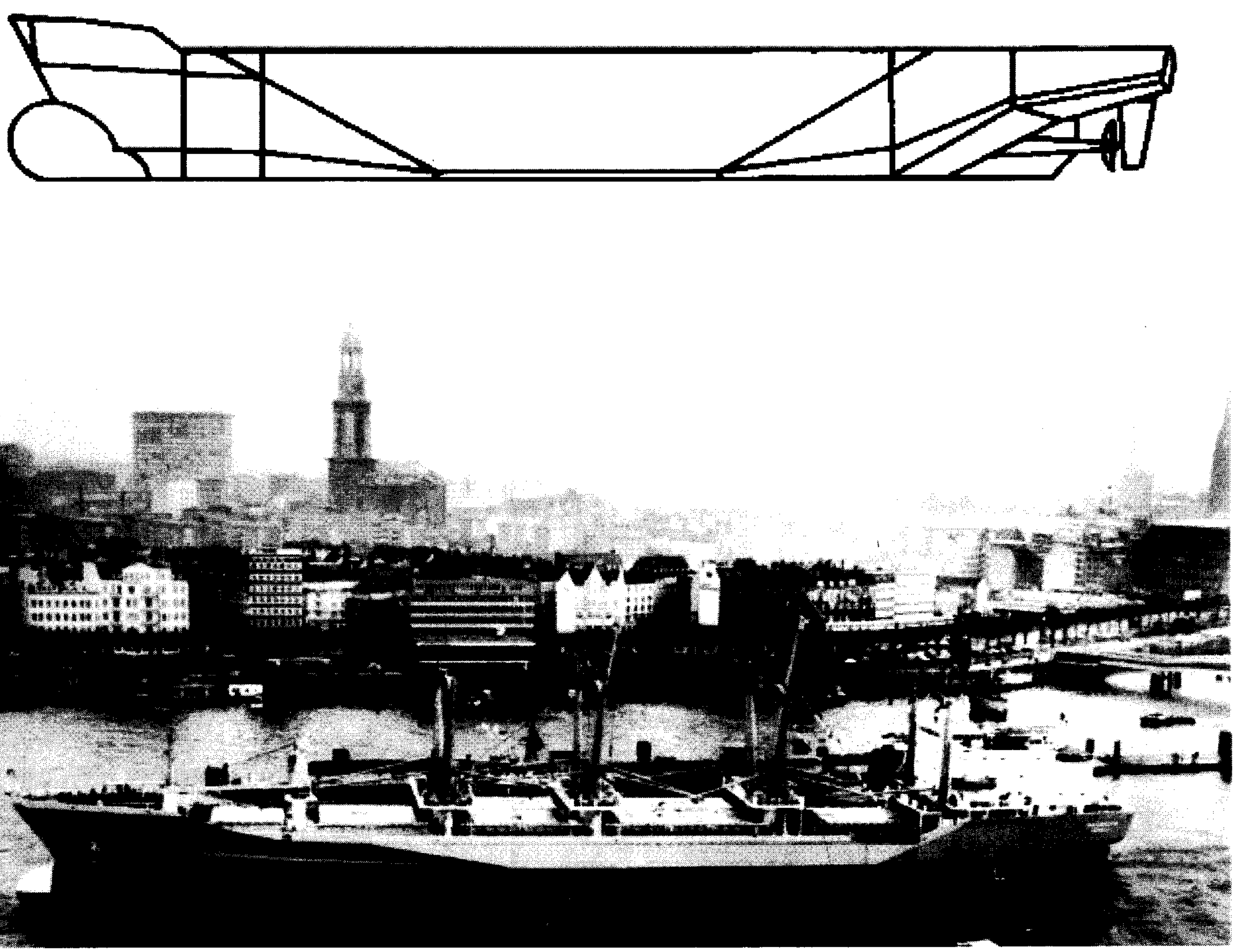


Figure 14.18 *Pioneer* ship of Blohm & Voss

- The Condock I featured many flat plates also in the regions on the ship ends (31,32). The bilge radius was constant over the whole ship length. The centers of the bilge radii were located, except for some transition zones, on straight lines. The stern ended in a flat region. This minimized the bending work for the hull plates.
- The U.S. Maritime Administration conducted research on a low-cost, general cargo ship, simplified and designed for mass production to support the transport demands during the Vietnam war. The research resulted in the Pacer design (33).
- In 1969, Mario Andrea patented an extremely simplified hull, the *helical ship.* The helical ship consisted of flat plates, plates with curvature in a single plane, and rectangular sections with the exception of the underwater portions of bow and stern, which were helical in shape. Preliminary model tests indicated again a drastic increase in power requirements outweighing any improvements in design.
- Burmeister & Wain developed a hull design for bulkers and OBOs which, except for small regions at the ship ends, consists of single-curvature plates (Figure 14.19) (34). The bow was designed parabolically with straight sections.
- Schenzle (35) presents in the Indosail project (Figure 14.20), a hull form consisting predominantly of single-curvature and flat plates.
- Wilkins et al. (36) describe a ship design for a U.S. Navy amphibious assault ship. The whole design was re-assessed in terms of producibility. The curvature of the hull reduced introducing some knuckles. The sections in the foreship were considerably straightened, the bulbous bow simplified. Many of the plates were flat or geometrically developable (conical or cylindrical). The most extensive simplifications were implemented above the waterline.
- The EconoForm design was developed in the mid-1990s and features all developable surfaces. Several similar designs have been developed for smaller ships which form a particular interesting market. They are usually built in series, so the ratio of production cost to development cost is higher than for big one-of-a-kind ships. Also bigger ships have naturally more flat plates and developable surfaces than smaller ships.

***Hull** curvature-a brief review of concepts* The local curvature of the hull to a large extent determines the amount of forming needed and thus the cost of producing a particular hull segment. The typical shapes of plating found on the hull of ships are shown in Figure 14.21.

Some concepts of hull form design for producibility thus follows directly from an analysis of hull curvature properties.

The curvature in any point of a surface is defined by the direction and magnitude of the maximum curvature and the minimum curvature perpendicular to the maximum curvature. These two values are denoted as principal curvatures. The sign of the curvature determines whether the surface is convex or concave. The Gaussian curvature K is defined as the product of the two principal curvatures:

$K > 0$ convex or concave surface
$K = 0$ developable surface
$K < 0$ saddle-shaped surface involving reverse curvature

A plate is *developable* when one of the principal curvatures is zero over its whole extent. This includes the trivial case when the plate is flat, that is, both principal curvature are zero. In addition, there are a number of important special cases for developable surfaces:

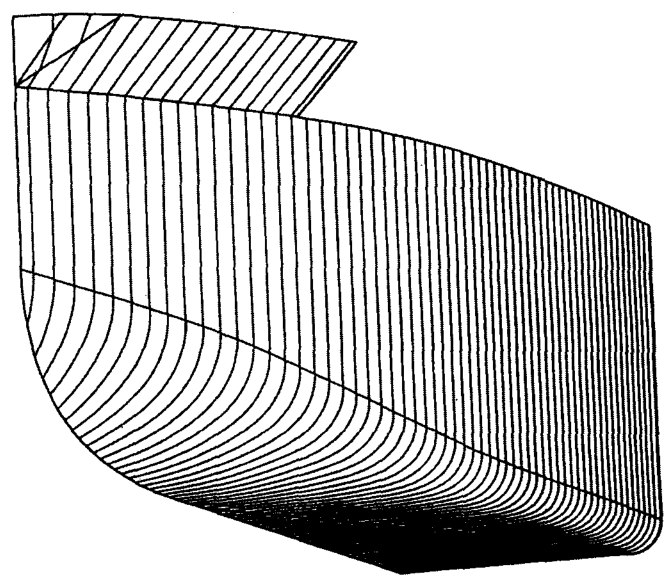


Figure 14.19 OBO Carrier (34)

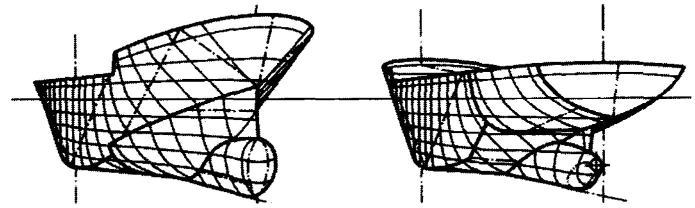


Figure 14.20 Ship Hull Composed only of Developable Surfaces (35)

- cylindrical surfaces; parallel cuts (waterlines or sections) have same contours, and
- conical surfaces; parallel cuts are geometrically similar but of different radii.

Although a sphere is a regular curved surface, it is not a developable surface as we all know from wrapping a sheet of paper around an apple or peeling an orange (Figure 14.22). The production solution is to make a sphere out of triangular cylindrical segments. A typical case of a combination of developable surfaces is the bulbous bow, which can be interpreted as a succession of conical surfaces andcylindrical segments (Figure 14.23). Developable surfaces do not include stretching or contracting of edges. This makes them particularly interesting in terms of producibility as the manufacturing process is then rather simple.

The complete hull surface of a number of small ships have been designed as developable surfaces. Rational Bezier or B-Splines can be used to produce developable curves, for example, Bodduluri and Ravani (37).

For a more detailed presentation on parametric surfaces and the definitions of surface curvatures, the reader is referred to Farin (38), Nowacki and Kaklis (39).

General producibility principles in ship hull form design
Aspects of easy production for the ship hull can be roughly classified into two groups:

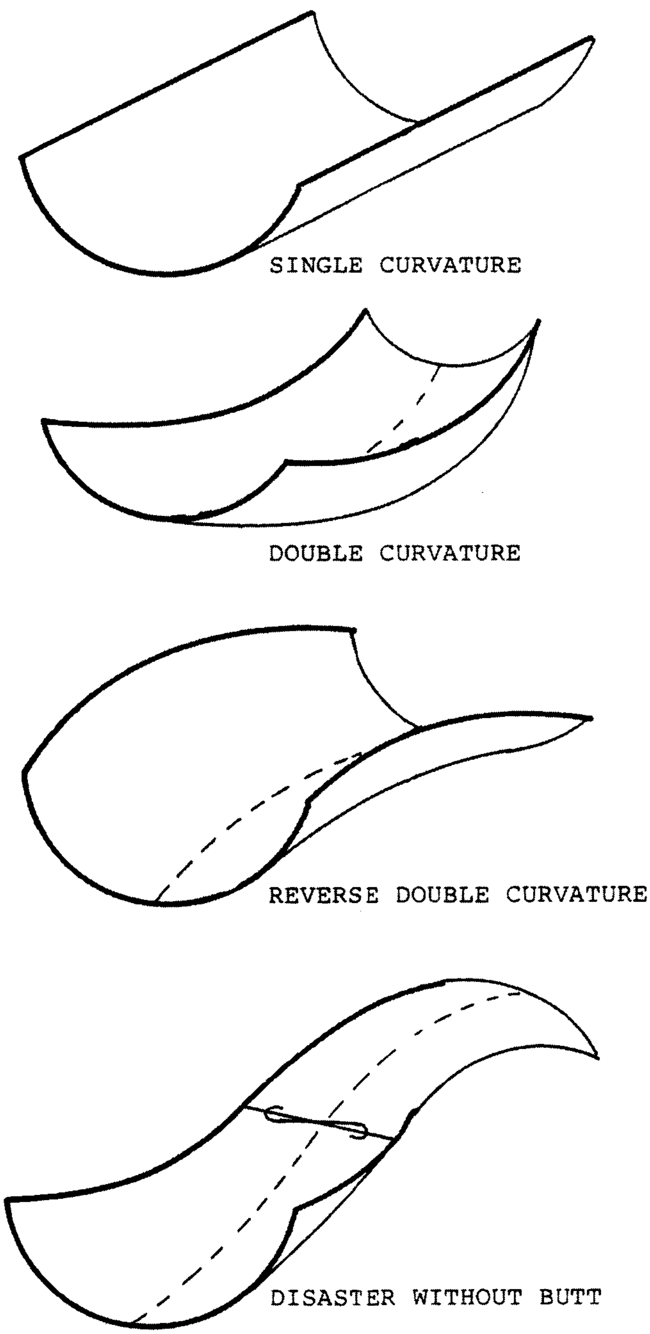


Figure 14.21 Plate Curvature

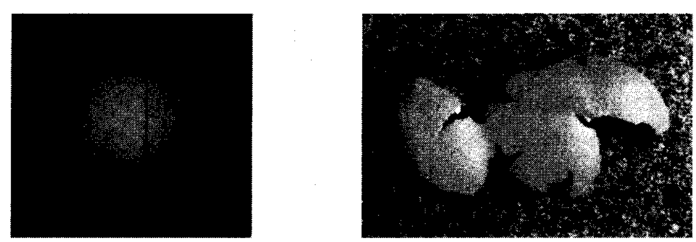


Figure 14.22 A Sphere is not a Developable Surface

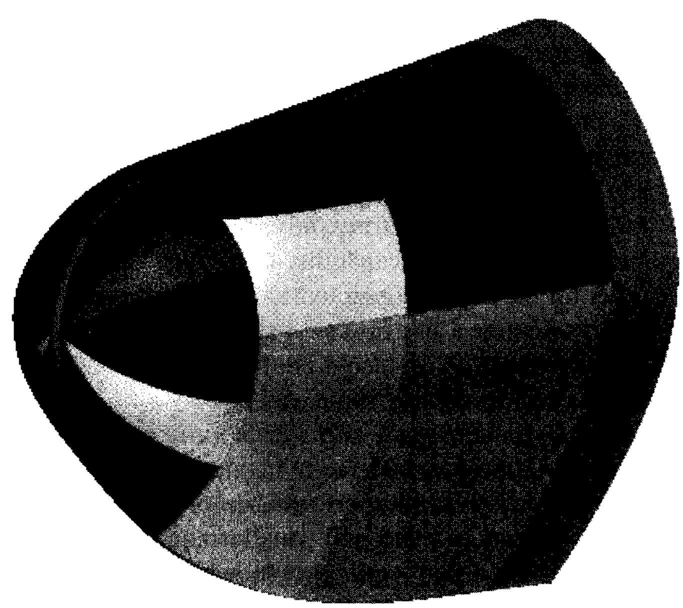


Figure 14.23 Bulbous Bow Designed in FAIRWAY Employing only Patches of Developable Surfaces

A compound curvature plate can be defined by measuring the following characteristics:

1. Longitudinal Backset Ratio (A/L)
2. Transverse Backset Ratio (B/W)
3. Twist over the length of the plate

These are shown below.

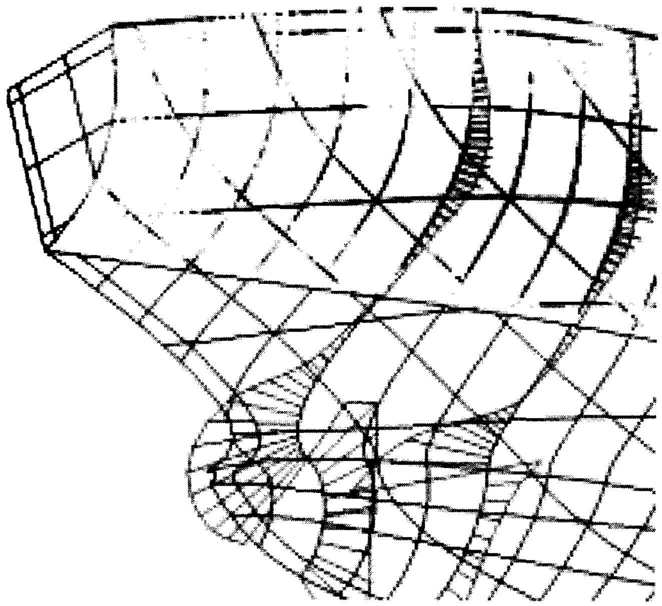


Figure 14.26 Porcupine Curvature Plot

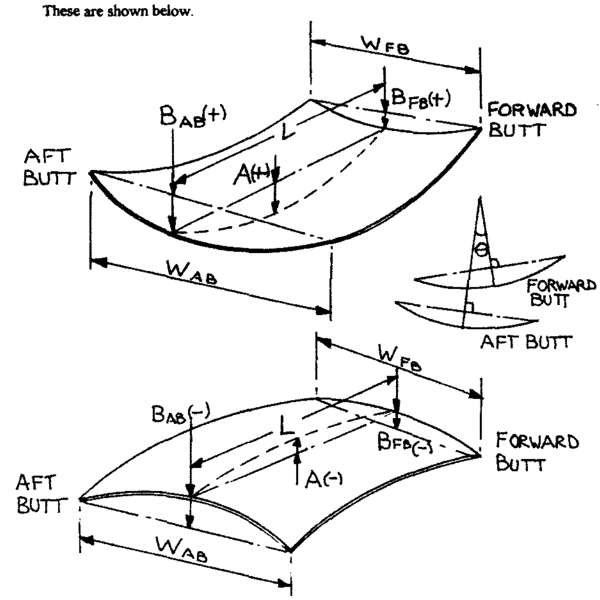
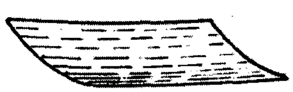
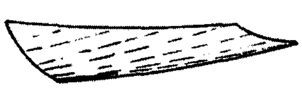
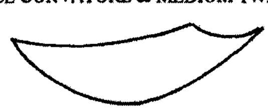
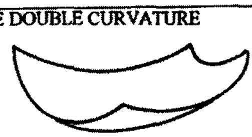
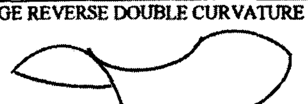
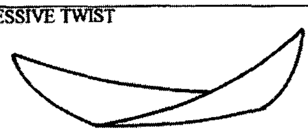


Figure 14.27 Shipyard Plate Curvature Capabilty Information Form: Sheet 1

CLASS	DESCRIPTION	LONGL BS RATIO	TRANSV BS RATIO	TWIST	REQUIRED FORMING	PRODUCIBILITY IMPROVEMENT
A	SMALL BACKSET NO TWIST 	0 ↓	0 ↓	0 ↓	ROLLER OR PRESS	
	SMALL BACKSET AND TWIST 	LESS THAN 0.02	LESS THAN 0.08	LESS THAN 10 DEGS	ROLLER OR PRESS THEN LINE HEATING OR LINE HEATING ONLY	
B	DOUBLE CURVATURE & MEDIUM TWIST 	0.02 ↓	0.08 ↓	10 DEGS ↓	ROLLER OR PRESS THEN LINE HEATING	RESTRAKE TO BRING WITHIN CLASS A CRITERIA
	REVERSE DBLE CURV & MEDIUM TWIST 	LESS THAN 0.04	LESS THAN 0.16	LESS THAN 30 DEGS		
C	LARGE DOUBLE CURVATURE 	MORE THAN 0.04	MORE THAN 0.16	0 ↓	ROLLER OR PRESS THEN LINE HEATING SPECIAL TEMPLATES REQUIRED TO ENSURE CORRECT FORMING	SPLIT INTO A NUMBER OF SMALLER PLATES EACH WITHIN CLASS A CRITERIA
	LARGE REVERSE DOUBLE CURVATURE 			30 DEGS		
	EXCESSIVE TWIST 	ALL THE ABOVE	ALL THE ABOVE	MORE THAN 30 DEGS	LINE HEATING ONLY	SPLIT INTO TWO PLATES BY PROVIDING BUTT AT SURFACE INFLECTION

NOTE - WHENEVER POSSIBLE DEFINE SHELL PLATES TO BE CLASS A PLATES

Figure 14.28 Shipyard Plate Curvature Capabilty Information Form: Sheet 2

Both frame/plate and plate/plate connections are easier to weld than in curved contours, Takeda et al. (44). Furthermore, straight sections eliminates bending. Repetition of frames reduces the number of different parts, which have to be manufactured, tracked, assembled and installed,

- *chines and knuckles* necessary to achieve a less complicated curvature should be located at unit breaks. Do not place chines or knuckles either at or between bulkheads and decks, but 20 cm to 30 cm from the bulkheads or decks where the breaks will be made. Chines or knuckles above the waterline do not influence the hydrodynamic performance! However, the fatigue strength ofthe knuckles should be investigated. A large number of chines or knuckles may lead to problems in fitting during assembly and in fatigue strength, and
- establish *unit breaks* early in the design process and locate them for repetitive design and construction of the units. The location of the unit breaks can be critical to cost reduction. For some ships, such as tankers and bulk carriers, much of the structure is repetitive. By careful location of the unit breaks, the units to be fabricated can be built from one set of plans with resultant savings in engineering and production man-hours. This not only allows for assembly-line type construction with the cost benefits of line production, but also reduces the man-hours required to design the ship. The early location of unit breaks provides another benefit by permitting the designer to locate the various items of machinery· and equipment in positions which facilitate unit outfitting. Any equipment which happens to be located across a break cannot be installed until after the units have been erected which makes it more costly. Joining the shell of two units is easier if the joint in one direction is stiff (near transverse structure, for example, deck or bulkhead) and the other is flexible (distant from rigid transverse structure).

The surfaces of modern hull geometries feature over wide areas a very small value for the smaller of the two principal curvatures. That is, the surface is almost developable and most plates can be cold formed. Only small changes in the hull form may be required to give developable hulls as proposed by Schenzle (35) (Figure 14.20). This would then have various positive effects on producibility:

- straight plate intersections reducing cutting work,
- increased in-plane welding suitable for robots, and
- straight stiffeners reducing forming work for stiffeners.

Especially the intermediate areas between flat regions in bottom and sides to the ship ends can benefit from such

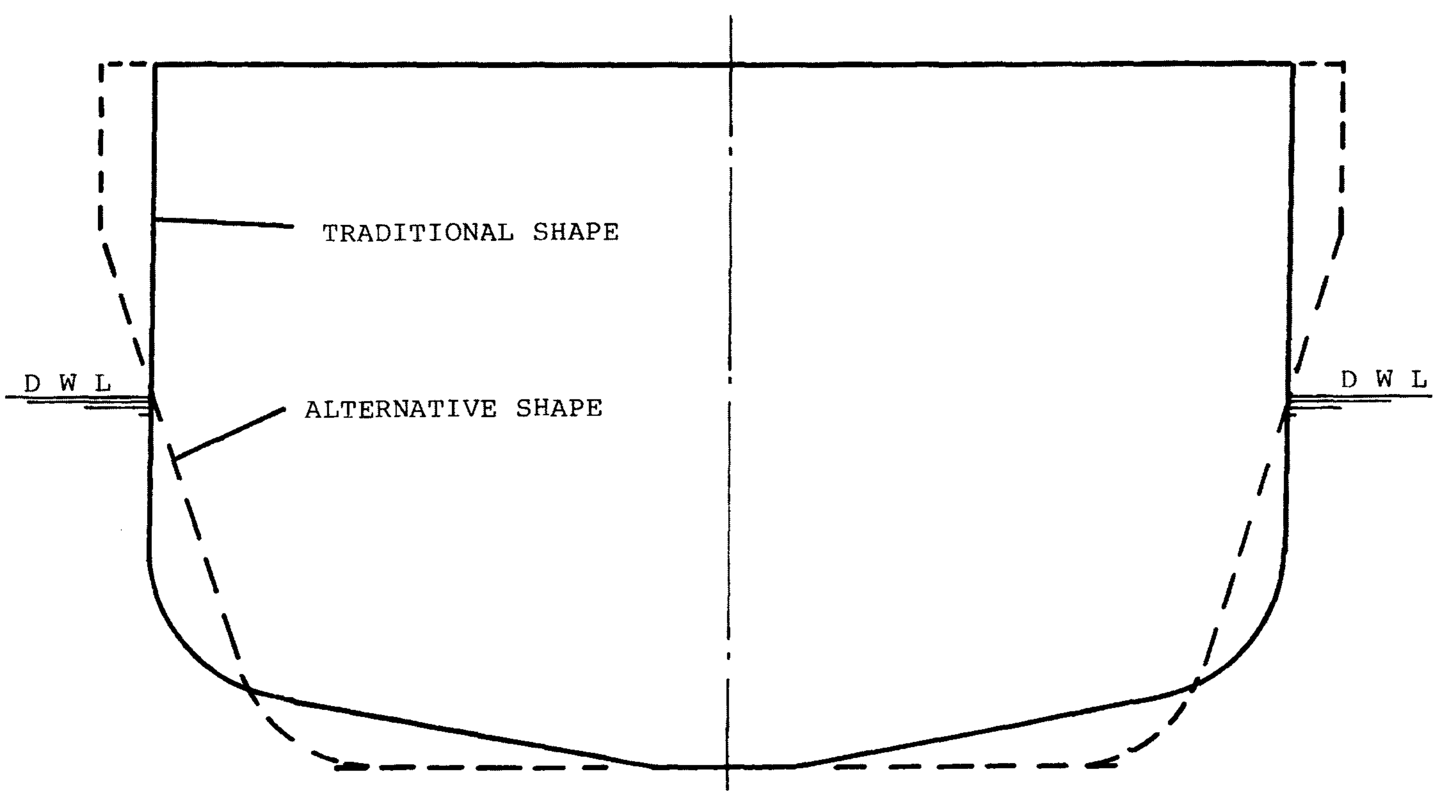


Figure 14.29 Flat Keel DFP Considerations

slight modifications which may have only negligible effects on the power requirements.

Fillt keel The width of the flat keel plate used to be a rule requirement for most classification societies. Many developers of lines still use these standards as guidance. For designs with rise of floor, the selected width becomes the knuckle/chine in the bottom. This approach is not correct! The flat keel should be at least wide enough to extend over the keel blocks to allow for welding of one of the seams as an erection seam when the blocks have a longitudinal break along the center of the ship. Where the bottom block spans the blocks, this is obviously not a factor. It is suggested that two other aspects must be considered to decide the width of the flat keel. The first is that the shipyard maximum plate width should be used as the flat keel width. The second is that if one of the seams is used as an *erection joint,* the flat keel width must suit the block joining method, including the design detail of the internal structure. These concepts are shown in Figure 14.29.

Maximum section shape The design of the maximum section of the hull considers bilge radius, rise of floor, and slope of sides. There is considerable guidance available to the ship designer on the maximum section coefficient based on resistance aspects. Obviously, the required coefficient can be satisfied by a combination of bilge radius, rise of floor, and even sloping sides (Figure 14.30).

The bilge radius should be selected so that the side block erection joint is above the tangent of the ship's side to the bilge radius, and above the tank top. In single bottom ships it may be preferable to select the bottom bilge radius seam as the erection joint and then the radius should suit this. The use of conic sections for the bilge shape as it moves forward and aft of the maximum section would result in the bilge shape being an ellipse and not a circle. The designer must appreciate this fact so that the intent to have circular sections can be correctly incorporated into the lines. If this is not done it may result in significant increase in work content as the shell plates must be formed to elliptical roll sets instead of a simple radius.

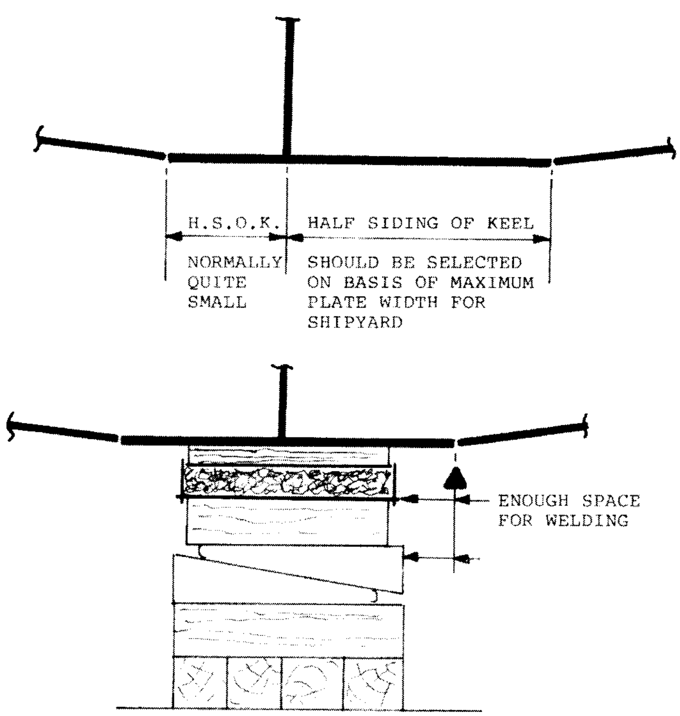


Figure 14.30 Alternative Maximum Section Shape for DFP Consideration

Single-screw skeg The afterbody lines of a single-screw ship are selected to provide low resistance and good flow to the propeller. Normal single-screw aftbodies are another part of the hull where reverse curvature is found. This reverse curvature can be eliminated by carefully locating plate seams and butts at the transfer lines from convex double curvature plates to concave plates. Even though double curvature plates have less work content than reverse curvature plates, the work content is still significant. One way to reduce the work content of the afterbody even further is to separate it into two parts, namely the main hull and a *skeg.* This can be done in two ways. The first way is to attempt to follow the normal single-screw hull form as closely as possible by incorporating a chine or *multichines,* joined in section by straight lines or simple sections, as shown in Figure 14.31.

The chines would lie in flow lines to prevent cross flow turbulence as much as possible. The second way, is to design the afterbody as a *cut-up stern* type, and add on a skeg as shown in Figure 14.32. Both approaches can usually be used without any adverse impact on propulsion power. However, the latter approach has the least work content.

Bulbous bows From a producibility point of view, the preferred shape of the bulb in the transverse plane is a circle. This shape can have some operating disadvantages, such as bottom slamming in a seaway. The next preferred shape that does not have the slamming problem is an inverted teardrop, but it has higher work content than the circular shape. A good compromise between design and production requirements is an inverted teardrop constructed from parts of two cylinders, two spheres (flat segments), a cone and two flats (Figure 14.33). A similar approach to developing producible details should be applied to other types of bulbous bows for large slow speed full hull form ships, such as tankers. Par-

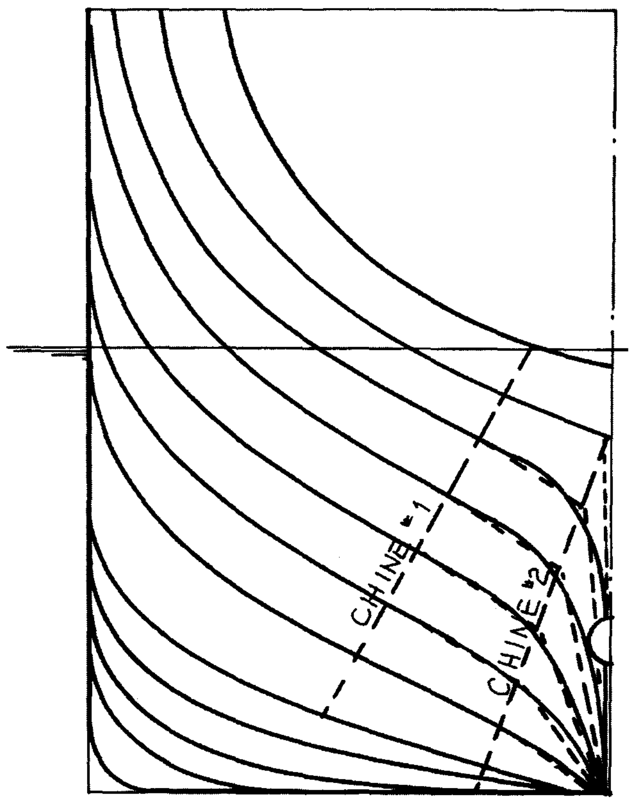


Figure 14.31 Use of Chines to Simplify Stern Construction

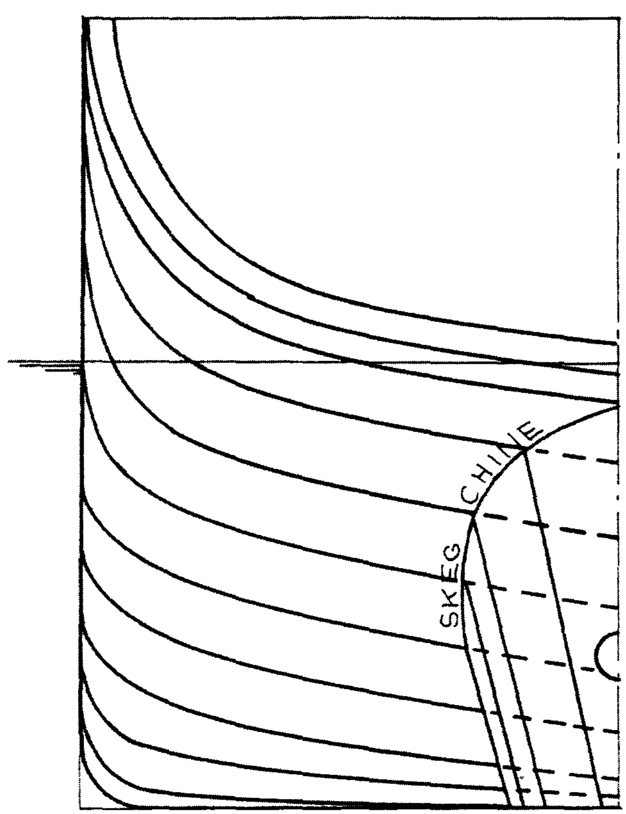


Figure 14.32 Use of Skeg to Simplify Stern Construction

tial stem castings have been used for bulbous bows where they are faired into the upper stem and shell. The casting can be eliminated by making the bulb to shell conneqion a chine (Figure 14.34).

Knuckles and chines Many ship designers utilize chine hull form designs on the assumption that they are easier to build than round bilge forms. Although this is generally true for small ships, it is not always appreciated that chines can add work content to a design. Before discussing this further, it is necessary to understand the difference between chines and knuckles. A formal definition of a chine is that it is the intersection of the bottom and side shell below the load waterline. However, it is usually used for any shell intersection curve, and in the case of double chine hull forms, reference is made to upper and lower chines. A chine is always on the shell and nowhere else. A chine is usually a curve in at least one plane. A knuckle can be anywhere on the ship. However, a knuckle is a straight line in two planes. Sometimes a chine located in the forebody above the load waterline is incorrectly identified as a knuckle because in profile it is a straight line. However, in plan view it is a curve.

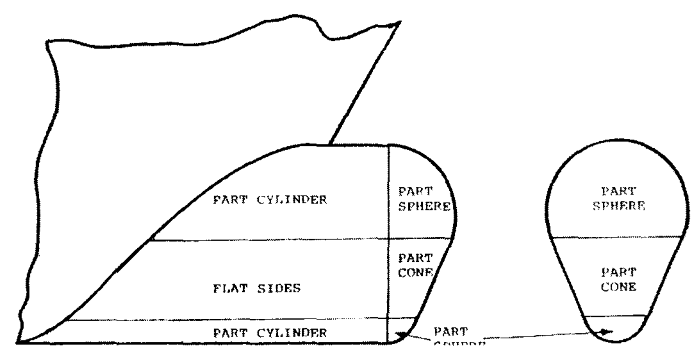


Figure 14.33 Bulbous Bow Using Regular Shape

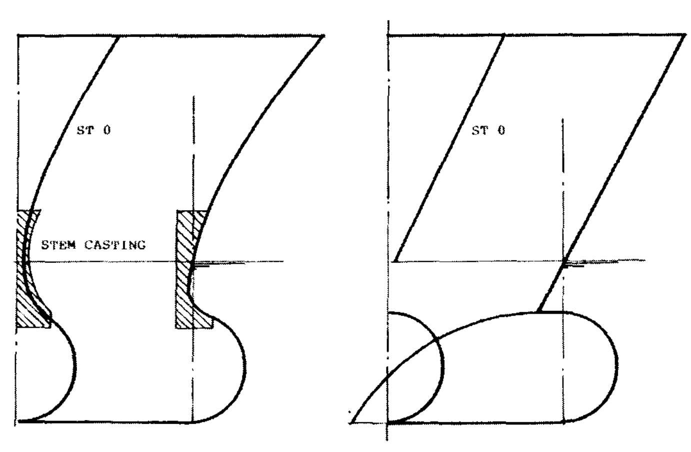


Figure 14.34 Faired versus Chine Bulbous Bow

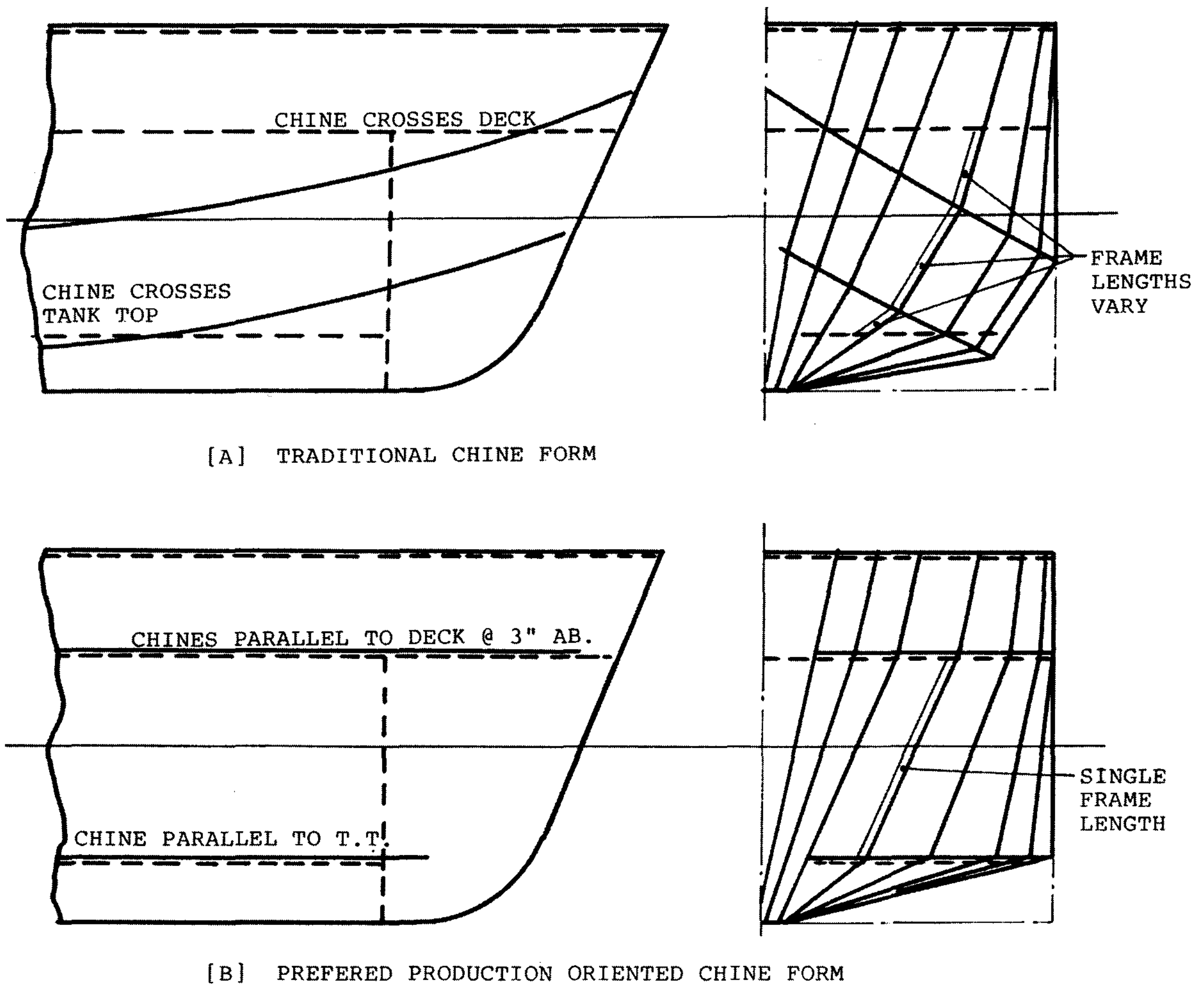


Figure 14.35 Hard Chine Producibility Considerations

When a chine is introduced into a design, and it is curved in the profile view, it can present a problem if the ship is constructed in blocks, as the chine is an obvious block erection joint. In addition, a chine that crosses a deck line introduces additional work content due to construction design details, including varying frame lengths and additional frame brackets. Chines are often located to follow flow lines in order to minimize any resistance increase. However, it is better, from a producibility point of view, to locate the chine parallel to the baseline/tank top/decks, as this enables the chines to be used as simple block joints and for simple alignment of the blocks. It also permits standardization of design details for floors, frames, brackets, etc. These concepts are shown in Figure 14.35, which also shows the problems with current chine shapes.

14.3.3.2 Arrangement design

When developing the arrangement of a ship, decisions must be made regarding the shaping of the hull, the location of cargo tanks, machinery spaces, holds, tanks and their contents, number of decks in the hull, number of flats in the machinery space, cargo handling gear type and capacity, accommodation layout, etc. It is, therefore, obvious that the development of the arrangement of a ship has a significant influence on its total construction work content. Yet it is usually performed with minimum production input. The construction work content is greatly affected by design decisions on the following aspects.

Bow The bow of a ship is one of the areas where designers regularly incorporate reverse curvature, apparently without any concern for its work content and thus cost. One only needs to look at a few ships to see this. Curved stems may be aesthetically pleasing but their cost must be appreciated. Even slight departures from a straight-line stem will add to the difficulty in fabricating it. The simplest above the water stem is one formed from cone (Figure 14.36).

This will give elliptical waterline endings, NOT circular, as most designers' use.

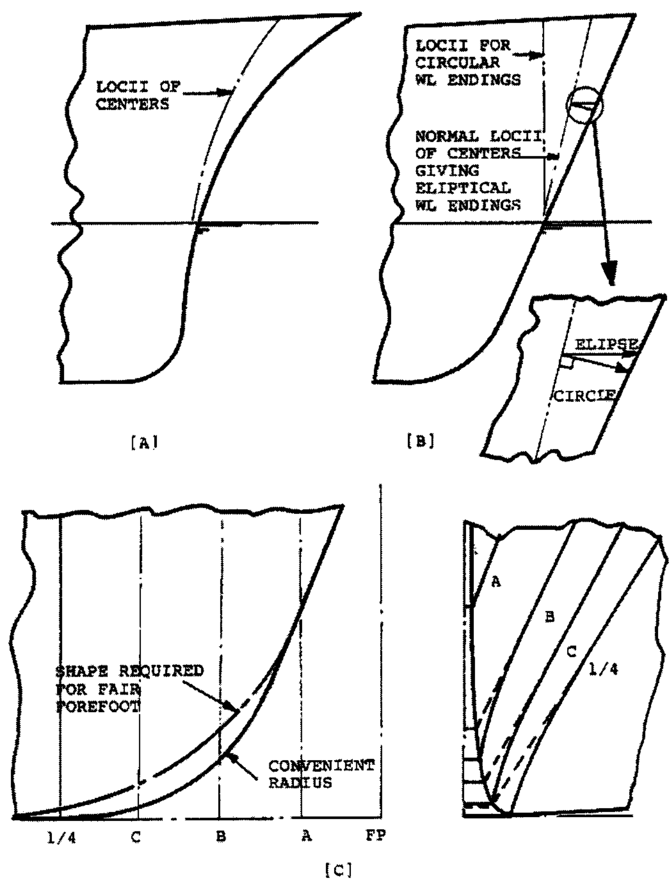


Figure 14.36 Stem Design for Production

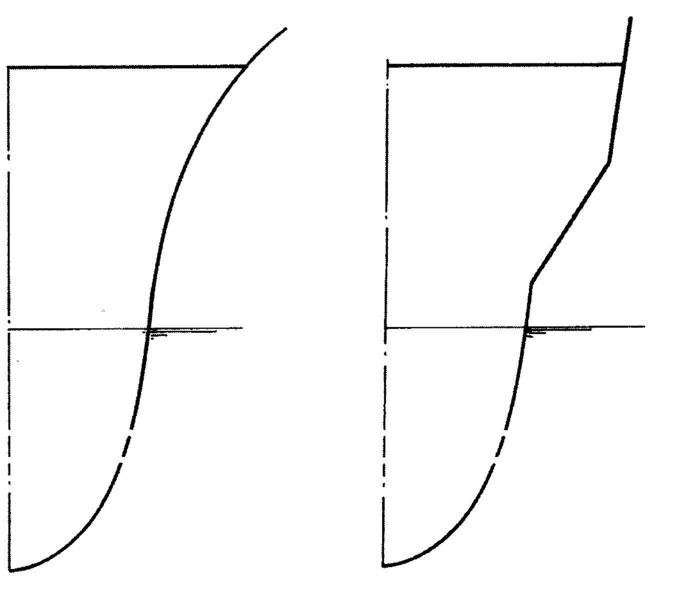


Figure 14.37 DFP for Bow Flare

Figure 14.37 shows a DFP approach to provide flare in the fore end of a ship. Figure 14.38 shows the result from applying DFP principles to the bow of an offshore supply vessel.

Stern The term *stern* usually covers two important independent but obviously connected items, namely the propeller aperture and the rudder arrangement, and that portion which is mostly above the design waterline aft of the rudder stock centerline.

The single-screw propeller aperture has evolved from early counter stem combined rudderpost types to the *open* or

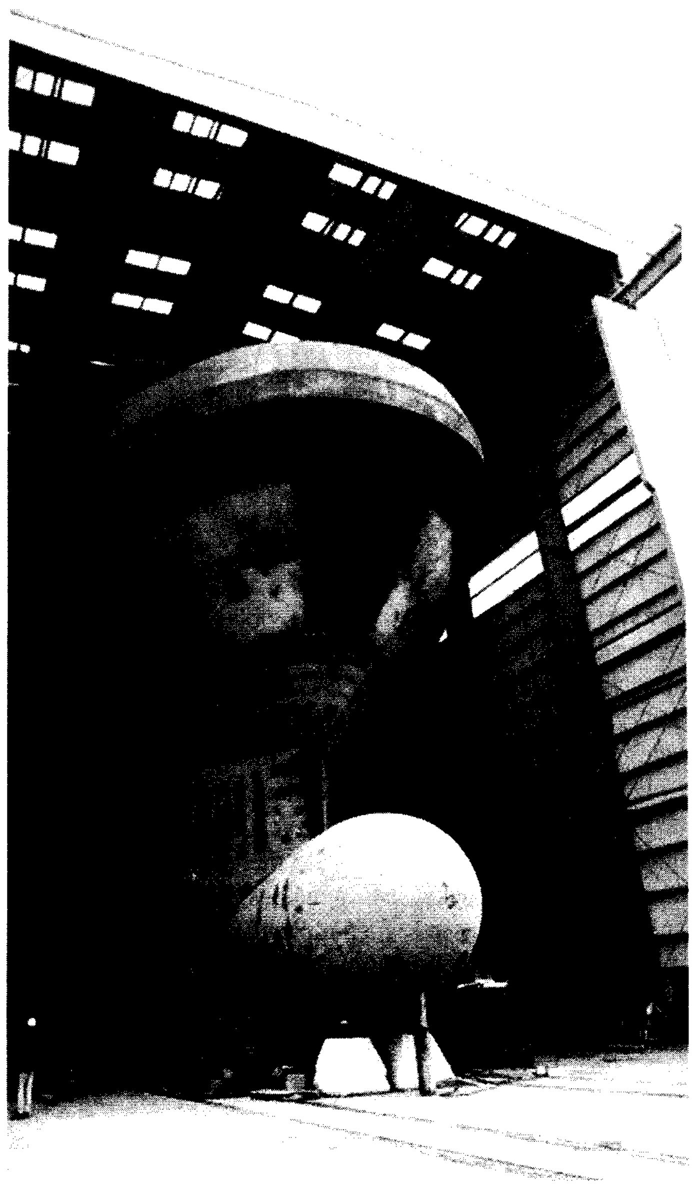


Figure 14.38 DFP Bow

Mariner style with spade or horn rudders. The design approach tended to favor *closed* apertures to reduce the size of the rudderstock to the minimum. However, even though it results in the largest rudderstock, spade rudders have the least work content if properly integrated in the design of the stern structure and if modern bearings are utilized. This can be seen by comparing all the parts and the various work sequences involved in both approaches as is done in Figure 14.39.

The upper stern development proceeded from the counter stern to the cruiser and then transom. Merchant ship designers adopted the transom stern because of its obvious economy, but also as it maintained deck width aft which was important in deck cargo ships, such as container ships and ships with aft deckhouses.

Unfortunately, designers still introduce aspects, which cause additional work content for transom sterns, by sloping it in profile and providing curvature in plan view as well as large radius corner connections between shell and transom. The design can be simplified by providing a vertical and flat transom, such as shown in Figures 14.40.

***Hold** or tank length* The frame spacing should be constant throughout the ship's length with the exception of the peaks, where the usual practice of incorporating smaller spacing is required by classification society rules. In the case of bulk carriers and general cargo ships, some designers deliberately vary the lengths ofthe different holds and tweendecks to equalize the loading and unloading times (45).

It is suggested that the length of the holds or tanks should be constant throughout the ship so that they can be divided into standard structural blocks and then simply duplicated as required. For example, in a ship with five holds of which three are in the parallel body and each hold has four blocks, then only four different structural block drawings need be prepared for three holds. If on the other hand the hold lengths are all different, then twelve structural block drawings are required. When the standard hold concept is carried over into lofting, process planning and actual construction, the labor and time savings multiply quickly.

This approach is simply applying Group Technology on a macro level during Basic Design, thus ensuring it can be utilized at the micro level during Product Engineering, lofting processing and workstation manufacturing. If it is necessary to vary the length of some holds or tanks, the length should be one or two web frame spaces more or less than the standard length so that the standard drawings can be simply extended to the non-standard length.

Engine room location In small ships the engine room can be located anywhere in the length that provides a workable loading/trim relationship for the intended operations.

For large ships the engine room is usually located aft of amidships. A popular location for the engine room in cargo ships is the two-thirds aft position (46). In all cases the obvious producibility factors to consider are:

- length of shafting,
- engine room is not suitable for standardization of arrangement and structure. Therefore, the engine room should be located in the part of the ship least suitable for standardization, that is, the ends,

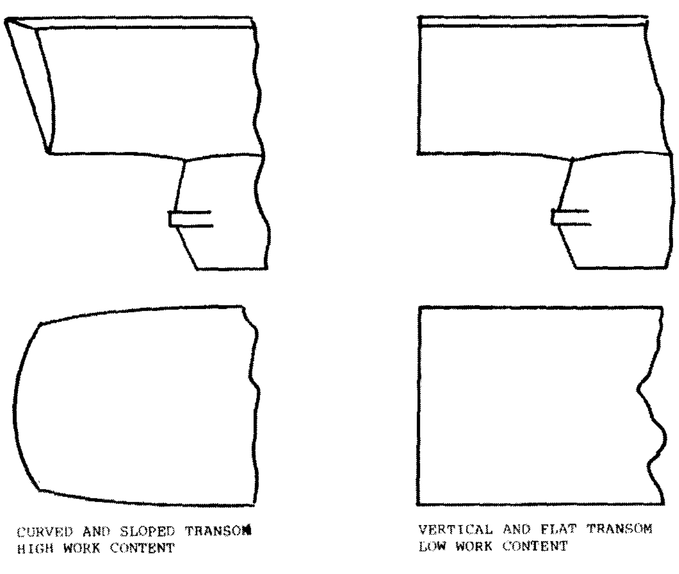


Figure 14.39 Rudder Type Selection for Producibility

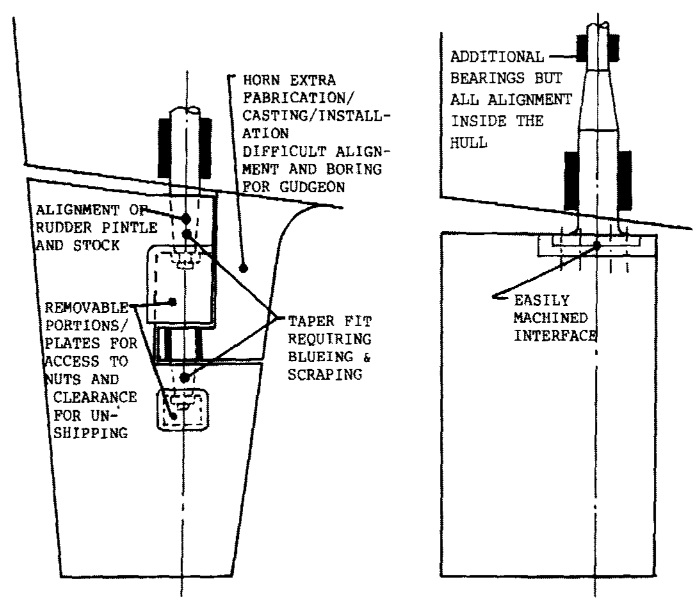


Figure 14.40 Stern Design for Production Considerations

- a shaft tunnel or alley is needed except for the all aft location, and
- an all aft deckhouse requires more tiers to provide adequate line of sight over the bow.

Before the recent skyrocketing increase in fuel cost, a number of novel machinery arrangements were developed, usually for novel ships, but sometimes for traditional ships such as tankers and bulk carriers. They were proposed for both reductions in material and operational costs as well as ease of construction. Some of these, which impacted productivity, were:

- split engine rooms above main deck with azmuthing propulsors,
- propulsion engines in twin skegs, and
- gas turbine/electric with GT generators above main deck.

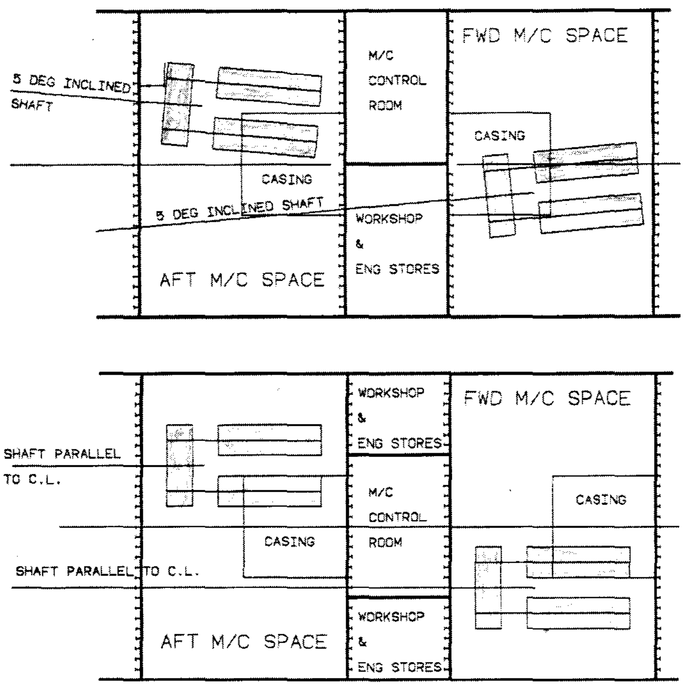


Figure 14.41 Machinery Room Arrangement Design

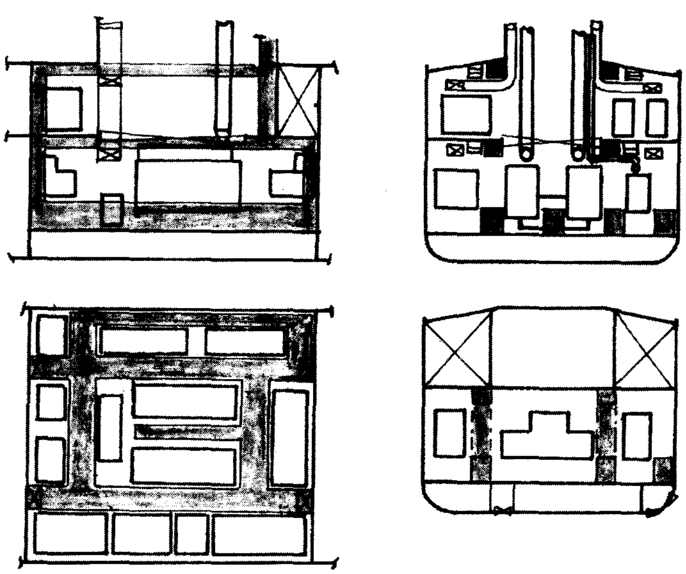


Figure 14.42 System Corridors

Machinery space arrangements It is essential that producibility be adequately considered during the development of the machinery space arrangement, not only in the equipment layout, but also for the surrounding structure. This can best be illustrated by an example. Figure 14.41 shows a typicallarge naval ship machinery arrangement consisting of two main machinery rooms and a central control room. The ideal, from a producibility point of view, is that both machinery arrangements should be identical.

The next best is to make the arrangements mirror images about the centerline of the ship. Obviously, only the aft space has two shafts in it. The forward space should simply be a mirror image of the aft space with the transiting shaft deleted. This is only possible if the shafts are parallel to each other and are horizontal. Unfortunately, this is often not possible, and the different spread angles and shaft slopes prevent exact mirror image spaces. Even in this case, the machinery rooms can still be mirror images except for the propulsion machinery setting.

The mirror image requirements also apply to the surrounding structure as well as the machinery and equipment. It can be seen from Figure 14.41(a) that duplicity of arrangements in the machinery rooms and surrounding structure was not attempted.

The following differences can be noted:

- the forward and aft transverse bulkheads in each room are stiffened on different sides,
- the casing is aft in one room and forward in another, and
- the control room is oriented differently to each room.

It is obviously easier to insulate a flush bulkhead than one with stifferenrs. This is because each stiffener has to be wrapped and the bulkhead insulation has to be cut into strips and installed between the stiffeners.

Figure 14.41(b) shows the same spaces with the arrangements developed to minimum necessary design, lofting and installation work content by incorporating duplicity as much as possible. It should be noted that the control room is now in the same relative transverse location for each room, but obviously it is not longitudinally.

The layout of the auxiliary machinery has a major producibility impact, and, therefore, it is important to arrange it in the most effective way. Today that means equipment package units, piping/ grating units and advanced outfitting. This is because advanced outfitting is driven by labor and schedule reduction goals, such as straight lengths of pipe, right angle pipe bends and combined distributive system/grating support units, all of which are manufactured in ideal shop conditions. However, the basic requirement in the design of engine rooms is the ease of machinery plant operation and maintenance and must be met and not impaired, regardless of the method of design and construction. Fortunately, the procedures used for developing advanced outfitting design are compatible with this basic requirement. If it is attempted to layout auxiliary machinery during Basic Design, it must be determined if advanced outfitting of the machinery spaces is intended as certain approaches must be followed if it is.

Even if advanced outfitting is not intended it is still a good design to approach the arrangement of the machinery space(s) into associated equipment groups and service corridors or zones (Figure 14.42).

It is suggested that only the unit boundary need be shown and the equipment within each boundary listed.

If the ship designer does not take such matters into consideration and prepare production oriented Contract Machinery Arrangements, it is strongly suggested that the document they prepare be designated as a Contract Guidance drawing, and only be used to show required equipment and any preferred layout.

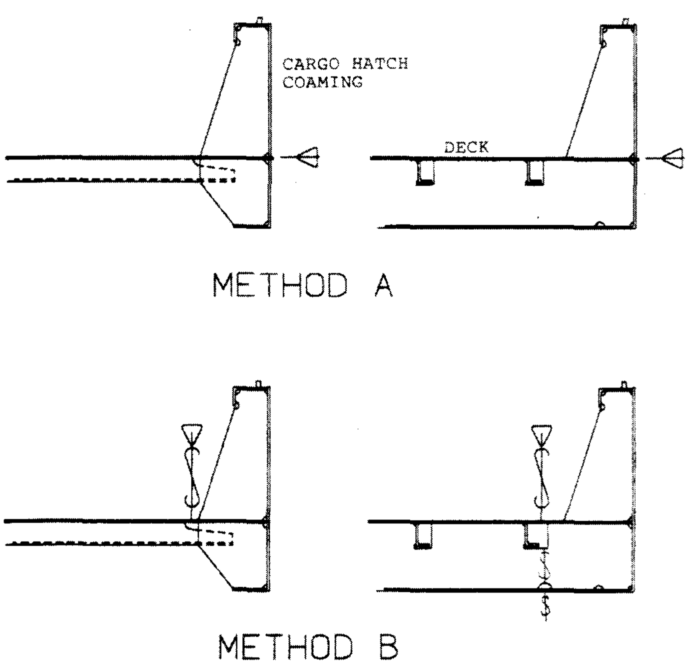


Figure 14.43 Hatch Installation Alternative

Cargo hatch sizes Standardization is the major producibility goal that should apply to cargo hatchways and hatch covers. All cargo hatches should be identical on a given ship or size of ship for a given shipyard. This would allow hatch coamings and covers to be designed and lofted only once, and to be built on a process flow basis. In addition to size and detail, the location of the hatches relative to the hold transverse bulkheads should be identical. The block erection sequence must also be decided at the earliest possible time, as it will obviously affect the design, and, in turn the work content for the hatch block and its installation. This can be seen from Figure 14.43, which details two possible design approaches that could be used.

Method A shows a hatch coaming that would be erected on top of the deck. It usually requires stock or green material to be left on the lower edge of the coaming for scribing to the deck. Also, the fillet welds of the coaming to the deck are not suitable for machine welding due to the brackets on the outboard side, and the absence of a work surface for the machine on the inside.

It will be necessary to provide staging inside the hatch coaming for workers welding the inside fillet.

Method B incorporates part of the deck in the hatch block. Any stock or green material would be on the inboard edges of the deck plating and the hatch block could be easily fitted using its deck plate edge as a guide to scribe the deck plate. It should be obvious that Method B allows machine welding of the deck seams and butts. No staging would be required although a personal lift may be required to fit the ceramic backing tape to the underside of the deck seams and butts.

Double bottom height The height of the double bottom is usually derived from the appropriate classification rule depth for the center vertical keel. Most double bottom spaces are small with difficult access for both workers and their tools. A problem often results from deciding the double bottom height based on the midship section shape. The bottom shape rises both forward and aft of the midship section, and this reduces the height in the double bottom outboard. Therefore, it is necessary to consider the double bottom height at the location where the hull shape reduces it to a minimum at the double bottom ends fore and aft and outboard.

It is possible to use a smaller double bottom height with transversely framed ships than with longitudinally framed ships. This is because for longitudinal framing, the transverse plate floors need to be deeper to allow for a reasonable distance between the longitudinal cutouts and access holes, as shown in Figure 14.44.

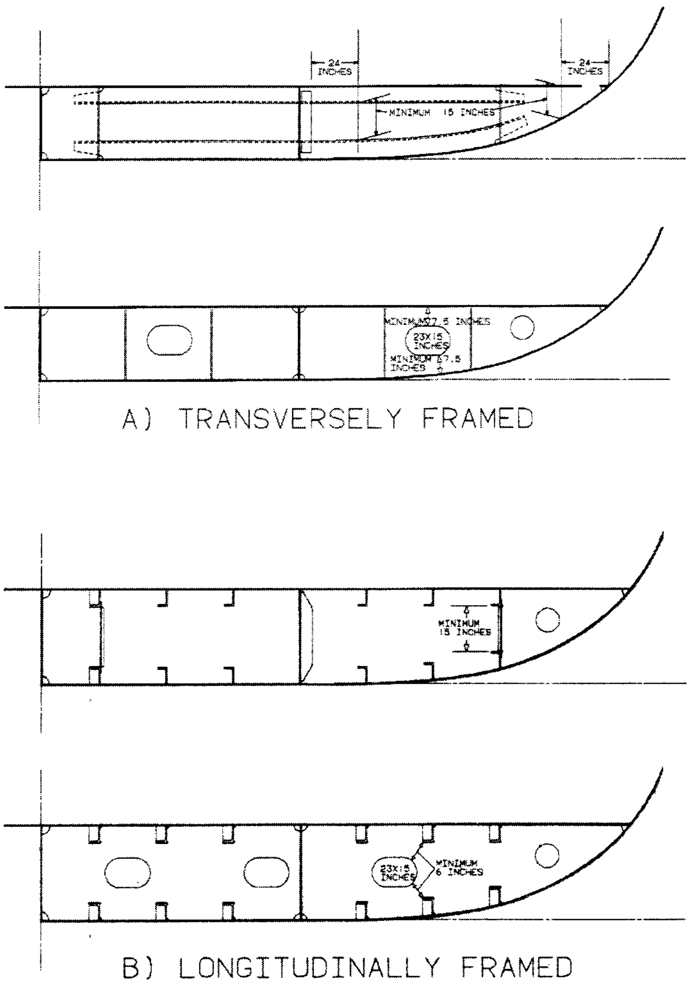


Figure 14.44 Factors Affecting Double Bottom Height

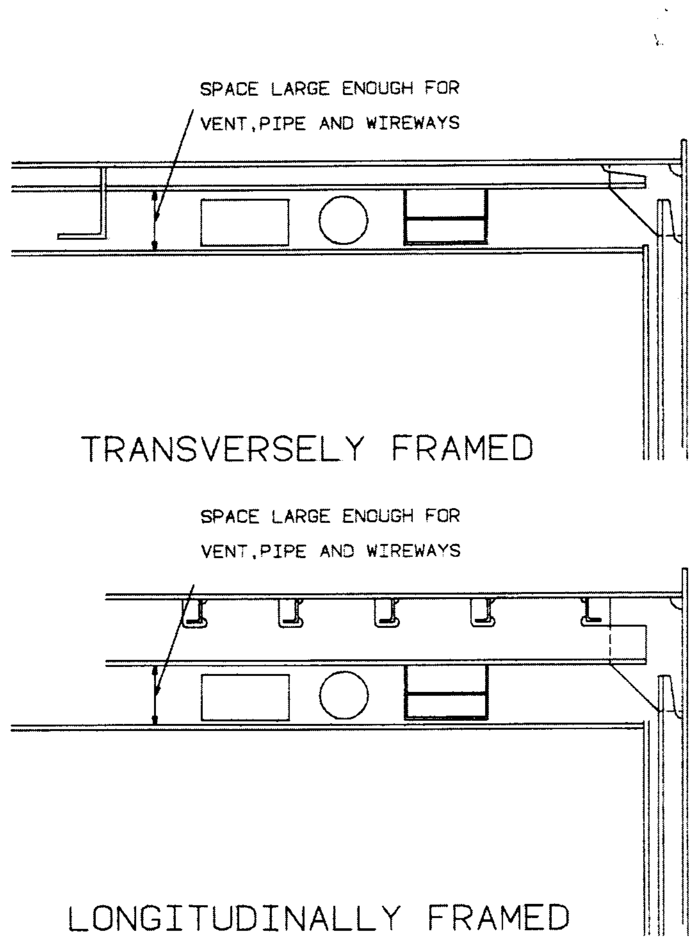


Figure 14.45 Required Space for Services

Tweendeck height The tweendeck heights may be decided by an operational requirement, such as use of standard pallets, hanging refrigerated meat, maximum number of boxes that can be stowed on top of each other, carriage of containers, RO-RO cargo, etc. In such cases the deck level must be selected to allow cost-effective design of ship structure.

In way of accommodation spaces, the tweendeck height should be selected to allow high productivity installation of the overhead vent ducting, piping and wiring. If it is difficult for the designer to squeeze such systems into the allowable space, it will be many times more difficult and use higher production man-hours for the worker to install the items. It is usually possible to use a smaller tweendeck height in accommodation spaces with transverse beams than longitudinals.

This is because longitudinally framed deep deck transverses add to the required height for fore-and-aft run services. Therefore, if the deck is longitudinally framed, additional tweendeck height should be provided. This requirement can be seen from Figure 14.45. Another possible approach, which is applicable to modem construction methods, is to select zones over service areas, passageways and toilets, and provide only the allowable minimum clear deck height in way of the zones (Figure 14.46). The specified clear deck height is maintained in all other areas.

Corregated and swedged bulkheads One very effective way to reduce work content as well as the weight of the structure of a design, is to use *corrugated* and *swedged* stiffening for bulkheads, deckhouse decks and sides (Figure 14.47). The work content is obviously reduced due to the reduction in the number of parts to be processed and assembled, and joint weld length, but it is also due to the elimination of weld deformation of thinner plate. There is an increase in work content due to the forming effort, but the net result is a significant work content reduction.

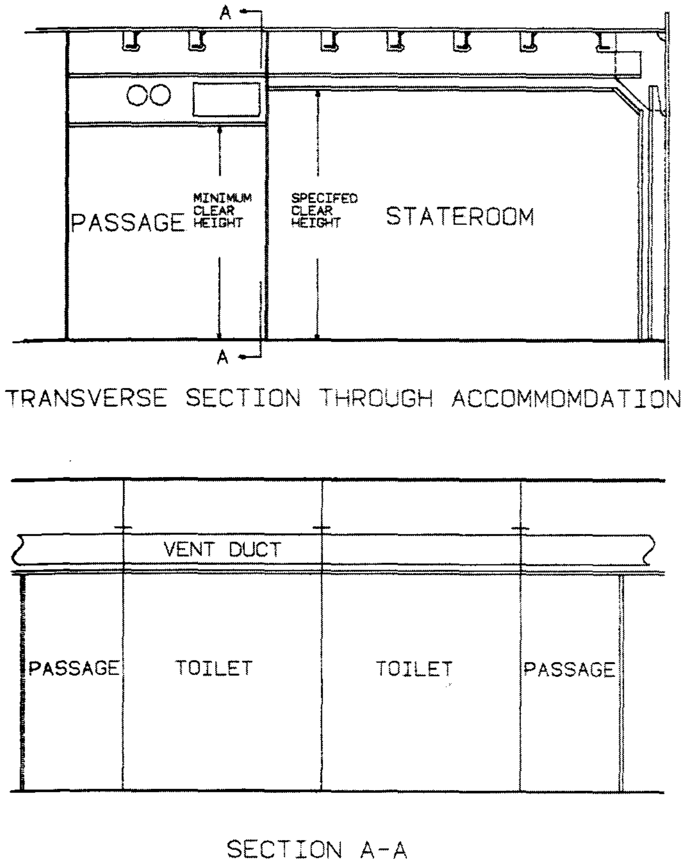


Figure 14.47 Alternative Stiffening Methods

Corrugated bulkheads can be effectively integrated with access ladders, pipe corridors, space ventilation and other items passing through the space. Corrugations for transverse bulkheads could be either vertical or horizontal, but for longitudinal bulkheads they must be horizontal. Finally corrugated bulkheads have the additional benefit of facilitating robotic tank washdown due to their elimination of stiffener shadow zones to the cleaning fluid.

Swedged bulkheads can be used for tweendeck structural bulkheads, and for all miscellaneous non-structural steel or aluminum bulkheads. Swedges must be vertical. Swedged stiffening could also be used for decks inside deckhouses. For short deckhouses with no influence on the ship's longitudinal hull girder strength, the swedges could run transversely. For long deckhouses, the swedges should run longitudinally. The decks would be swedged downwards and the trough formed by the swedge filled with deck covering underlayment.

One disadvantage of corrugated and swedged construction is that it prevents machine welding of the edges perpendicular to the corrugations or swedges to the connecting structure. This can be overcome for swedges by developing welding machines especially for this purpose, and in the case of swedges, by modifying the ends so that the intersecting edge is straight.

Location of block breaks and tank bulkheads From a production point of view, it would be ideal if the tanks in each erection block could be completed and tested before erection. This would enable any defects to be easily corrected on the block construction platens. This is not possible when common tank boundaries cross or are located at erection joints. Usually, only a portion of the tanks needs to be hydraulically tested, and then the erection joints should be located in the tanks that will not be hydraulically tested. In addition, if the tanks were to be coated, it would be preferable to have no block connecting welding which would damage the coating, thus requiring rework.

One way to achieve this ideal would be to provide cofferdams in way of erection joints. This would reduce the amount of usable space in the hull for tanks, and would increase the steel weight. The work content would also increase due to additional manholes, sounding tubes and air vents. However, it could still be a productivity net improvement depending on the design, extent of required testing and tank coatings. Figure 14.48 shows this concept.

Deckhouse shape and extent of weather decks Sloping house fronts, exterior decks along the sides and aft bulkhead, and sweeping side screens all add significant work content to the task of constructing a suitable deckhouse to accommodate the crew, and provide the necessary operating and service spaces.

While certain ships such as passenger and cruise ships can justify the additional cost of such aesthetic treatment, in general, they are unnecessary additional work content for all other types of ships. They not only increase the construction cost, but they also cost more to maintain during the ship's operational life.

The ship designer should develop simple deckhouse design utilizing vertical and flat deckhouse fronts, and provide exterior decks that are required only for the safe access and working of the ship. Figure 14.49 shows the two extremes, and the additional work content can be clearly seen.

Sheer and camber Eliminating sheer and camber results in a flat deck, which has less work content than a deck with both. This is due to eliminating the need to form the decks, the deck beams, angle the deck beams and form the deck

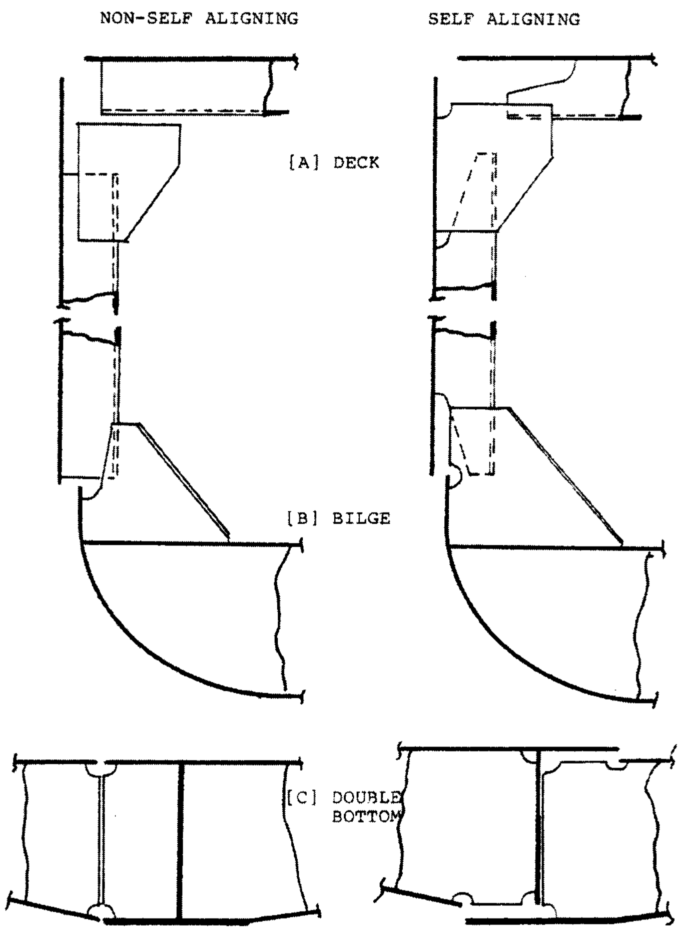


Figure 14.48 Block Breaks DFP Considerations

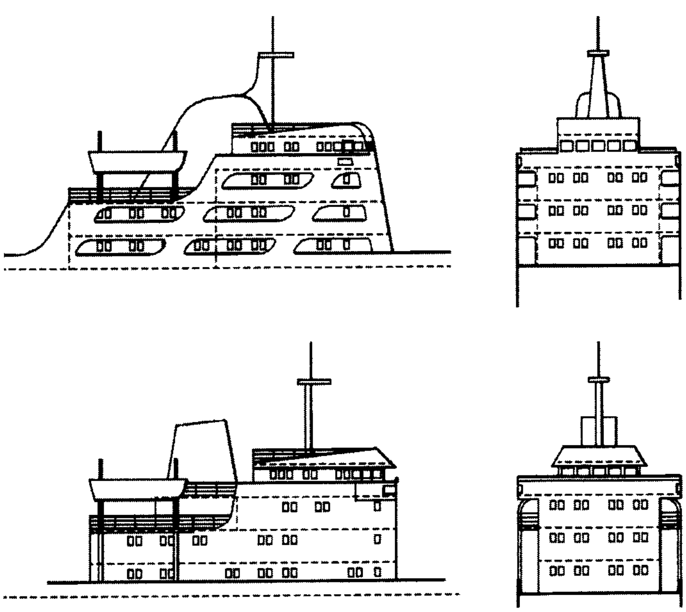


Figure 14.49 Aesthetic versus Cost Effective Deckhouse Design

girders. This applies to decks in the deckhouse and superstructure as well as the hull. For some designers and owners the elimination of sheer and/or camber is a \Very emotional matter and they argue that sheer and camber improve the seakeeping and other operational aspects of the ship. The other side logically argues that this is not the case because ships are seldom level when at sea, and even in port they usually have trim and heel.

Access for workers and equipment The arrangement designer must consider how the ship will actually be constructed, and provide adequate access and working levels, including permanently built-in solutions, for workers and their equipment during the construction and later maintenance of the ship. Some ideas in this regard are:

- service trunks, corridors or zone for deckhouses and above machinery spaces,
- cofferdam under deckhouses that will be constructed and outfitted completely before erection on the hull or between two blocks of a deckhouse erected in two tiers, and
- galleries in tankers, which eliminate need for staging (Figure 14.50).

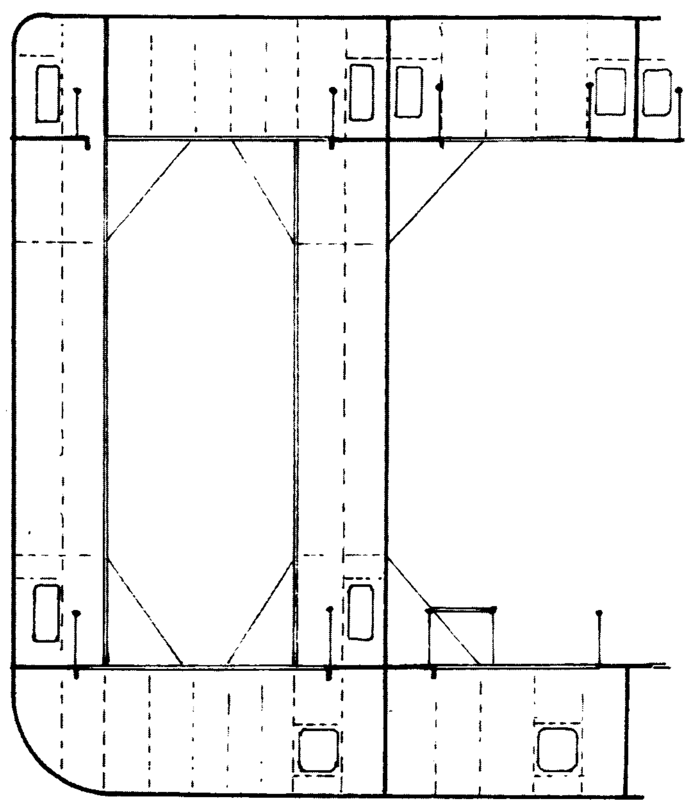


Figure 14.50 Built-in Access Galleries

Effect of admeasurement rules The application of the Admeasurement Rules has adversely affected the producibility of structural design for many years. Access holes in double bottom floors and girders, and to tanks have been restricted to 600 by 450 mm ovals. Lightening holes have likewise been restricted to 18 inch diameter, except in fuel tanks where 750 inch diameter holes are allowed providing they are strapped by installing a 40 mm wide flat bar horizontally across the middle of the hole.

This is an obvious work content increase that has no real design function. In the U.S., for small ships that benefit from being measured below 200, 300, 500 and 1600 Gross Registered Tons, various admeasurement reduction devices such as full depth plate floors on alternate frames, tonnage openings in cargo and accommodation spaces, and excess capacity of water ballast tanks all add significant work content to the ship.

The 1969 IMCO Tonnage Convention will eventually eliminate the unproductive additional labor and material cost for the larger U.S. built international voyage ships, as it does not allow any of the admeasurement reduction devices. By eliminating the tonnage reduction devices in larger ships, the ship designer will be free to utilize access and lightening holes to suit the shipyard's best approach to access for workers, equipment and material.

It is imperative that the arrangement designer be fully aware of the admeasurement method to be applied to the ship, and if it is the *new way*, to erase all *traditional* tonnage affected design details from the ship arrangement, and utilize instead details that improve productivity.

14.3.3.3 Structure

The design of ship structure is the process of applying rules and experience to integrate individual structural components into efficient and easily constructed subassemblies, assemblies, blocks and hull. Because it is a large part of the weight, construction man-hours and material cost, and also as it is relatively easy to design, more details are usually given for the structural part of a Contract Design than for any other discipline. Yet it is for the structure more than any other discipline that each shipyard must individually design to suit its own facility or else have its needs and preferences incorporated into the design during the preparation of the Contract Design. It is suggested that structural design, if prepared by a design agent for a Contract Design, be designated as *Guidance Only*, thus allowing the shipyard to utilize its own details. However, this has been proposed before (4,10) and it has not resulted in any change by Design Agents and Owners. In this situation, it is important that designers realize the impact of their design decisions.

Many ship structural designers use *Standard Structural Details,* which they may have *borrowed* from other designers in another shipyard. Or, for a naval ship, they may simply use naval ship standards, which are over 20 years old. Chances are that the decision to use a particular detail will be made without any regard to producibility requirements for the shipyard involved.

Remember that as there are a great number of connections between the structural components of a ship, the *best* design for one shipyard might not be the *best* for another. The *best* structural design detail depends on:

- block definition and erection methods,
- manual versus computer-aided lofting, and
- manual versus NIC cutting.
  - extent of automatic welding,
  - whether or not the shipyard has a panel line, and
  - facility and equipment.

However, the basic goal of Design for Production is to reduce work content, and the development of structural details should accomplish this goal. Before discussing some details, it is necessary to consider the selection of block boundaries.

Block definition When deciding block boundaries, a number of items must be considered, some obvious, and some not so obvious. These are:

- maximum block size,
- maximum block weight,
- block turning limitations,
- shell shape boundaries,
- access for workers and equipment required for joining blocks,
- extent of use of auto and semi-automatic machines,
- whether or not self-aligning,
- internal connection detail,
- framing method,
- plate straking direction,
- in line or staggered transverse breaks,
- maximum or standard plate/shape sizes,
- completion of adjacent spaces/tanks,
- blocking or shoring requirements,
- natural lifting points,
- use of *green* or stock material for fitting,
- large equipment arrangement and foundations to avoid overlapping block breaks, and
- design to eliminate plate or pin jigs.

The block boundaries should be located at natural plate butts and seams. Block breaks should be located to minimize erection work content.

14.3.4 Design for Production in Detailed Design

Design for Production in Detailed Design focuses on the preparation of design details that are production friendly and the use of production-oriented techniques to transmit and communicate design and engineering data to various users in a shipyard.

There are a number of production-friendly detailed design details that will be the same from shipyard to shipyard, but there are many more that will be unique to each shipyard depending on the ships to be built and the shipyard's facilities and capability. Therefore, the appropriate DFP for a given shipyard must be developed by the shipyard utilizing a team approach involving all departments involved in the decisions.

The Build Strategy Approach is a convenient way to accomplish this and it provides many benefits beyond the basic DFP. It is too late to begin DFP in the Detailed Design stage. Design for Production in Detailed Design builds on the Design for Production in Basic Design.

Keeping in mind that the detailed design stage is too late to apply the basic DFP, if it has been applied in basic design, then it is a natural extension for the design of the details of the product, in detailed design.

All functional areas are involved. Because structure is the major work content functional area in coinmercial ships it is always well covered. However, the DFP approach has to be applied to all areas consistently if the full benefit is to be achieved.

14.3.4.1 Structural details

The labor man-hours to construct the structure of a ship can be significantly reduced by proper attention to the design of the structural details. A number of structural details are examined in this context.

Stern Frame At one time most stern frames were designed as castings. This enabled complex shapes to be incorporated in the design, and also to provide an early-erected reference to build to when ships were constructed part by part on the building berth. A number of shipyards still fabricate the traditional stern frame. The widespread use of structural blocks necessitated the integration of the stern structural design. Therefore, the ship designer must select stern lines and propeller aperture shape to enable the stern block to be easily constructed and eliminated the need for separate and cast stern frames (Figure 14.51).

Block Breaks The basic guidance for block breaks was covered in DFP in Basic Design. In detailed design it is necessary to consider the details of the breaks.

Figure 14.52 through 14.54 show an approach for ship construction developed with DFP in mind. The layer con-

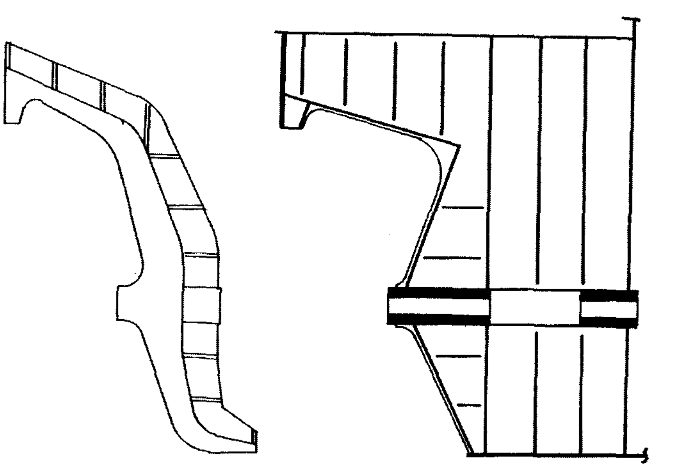


Figure 14.51 DFP Stern Frame Elimination

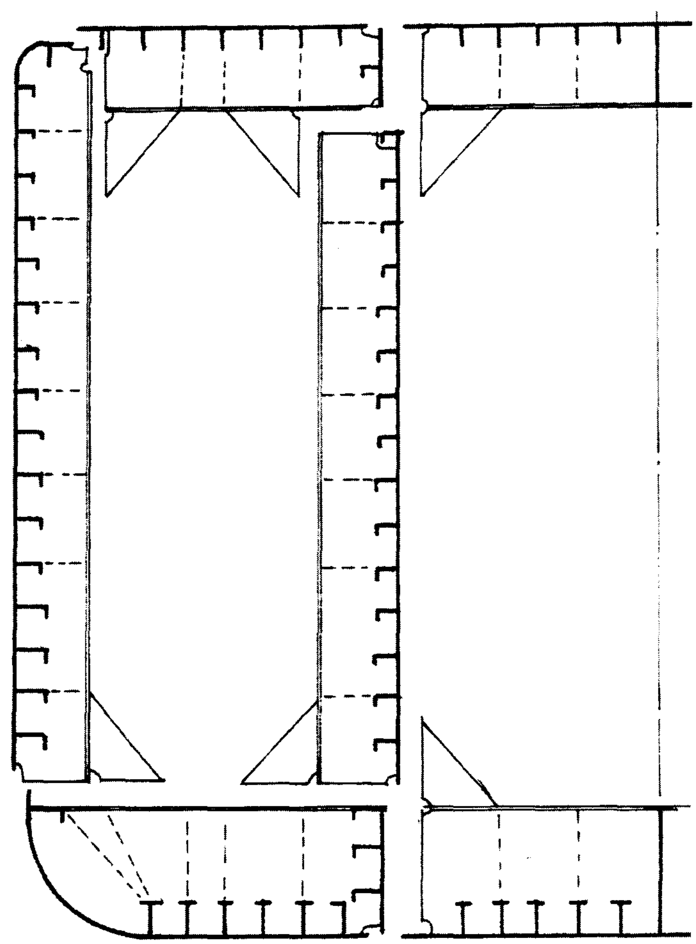


Figure 14.52 Layer Method for Tanker

cept can be applied to many ship types and in many locations. Its benefit is that the joining weld is a double fillet rather than a horizontal butt weld.

Figure 14.55 shows typical alternative approaches for the shell connections in way of block breaks and Figure 14.56 in way of block breaks in double bottom tanks.

Self-aligning Blocks Block breaks can be arranged to be either non-self-aligning or self-aligning. This is decided by the shipbuilder to suit erection preferences as shown in Figures 14.55 through 14.57.

***Plate** Straking* The obvious goal for plate straking is to standardize the plates. A standard plate should not only be identical in size but also in marking, beveling, etc. (Figure 14.58), thus providing significant reduction in engineering, lofting and production man-hours. This can only be accomplished by locating the stiffeners and webs/floors in the same position on each plate. To do this, two options are use of special tooling cost effective and possible. One is to consider stiffener and web spacing to suit the maximum width and length of plates to be used. The other is to select plate width and length to suit the desired stiffener and web spacing. For example, if a shipyard desires to use a maximum plate size of 16 by 4 meters, the spacing of the stiffeners will be given by $4/n_s$ and ofthe webs by 16/~) where both ns and nw must be whole numbers.

If, on the other hand, the shipyard wishes to use a stiffener spacing of 900 mm and web spacing of 3.5 meters, the 16 by 4 meter plate would not allow standard marking. The correct standard plate size for the desired spacing would be 14 meters in length and 3.6 meters in width. This example shows that when developing structural design, all the factors that can influence productivity, and thus cost must be included. It is pointless to spend time and money to standardize design and facilities and to lose much of the benefit by not understanding the impact of incorrect plate standardization.

Another problem not generally understood is the effect of shell plate straking on curved plate work content and material scrap. As previously mentioned in Subsection 14.3.3.1,

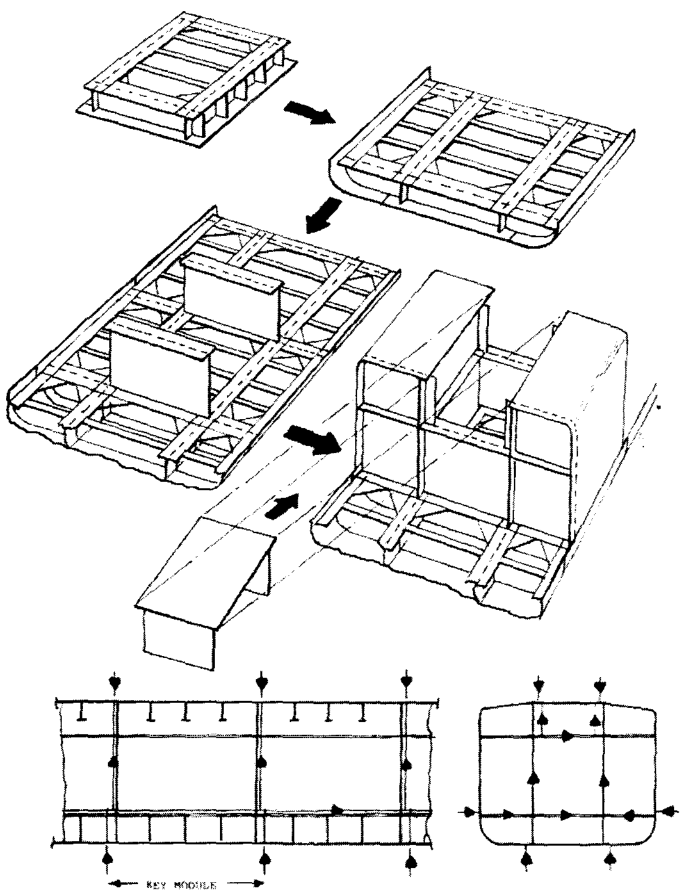


Figure 14.53 Block Erection Sequence for Layer Method Construction

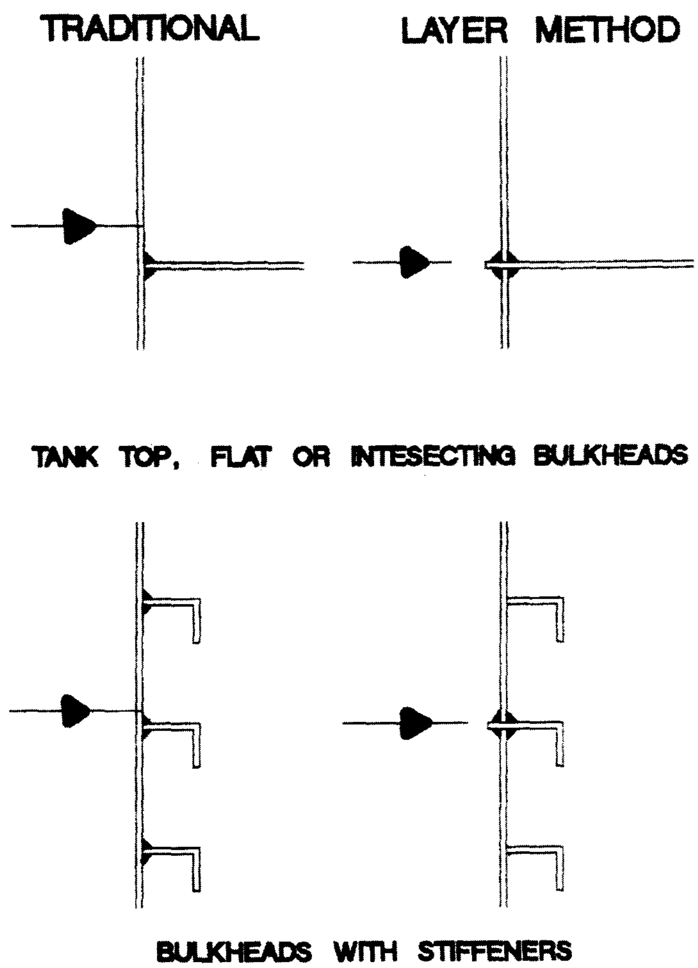


Figure 14.54 Details of Layer Method Joints

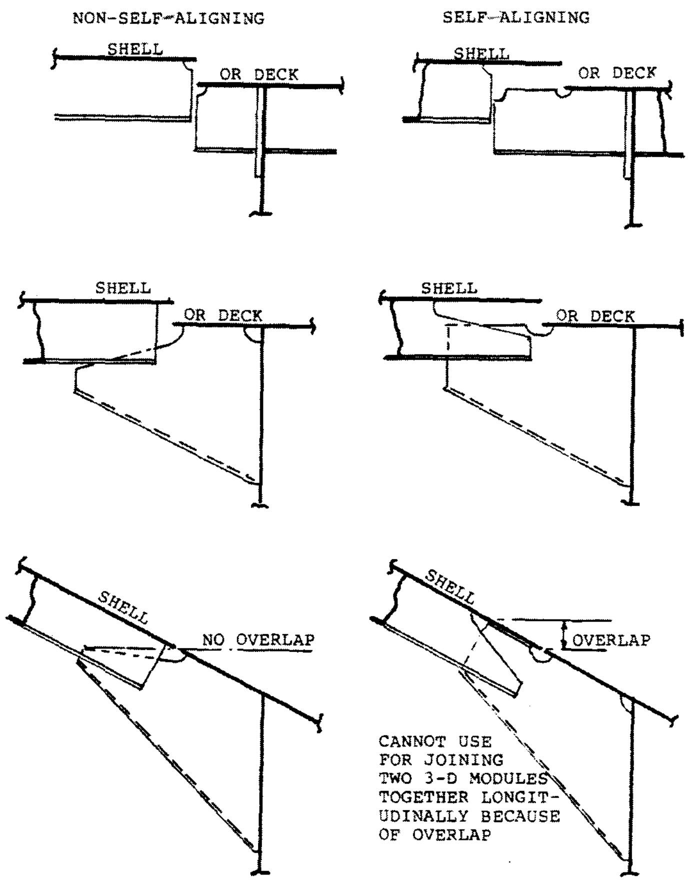


Figure 14.55 Shell Connect Alternatives in Way of Block Breaks

in the past straking was decided to follow the natural curvature of a ship as shown in Figure 14.59. Today, block construction has resulted in many plates having horizontal seems and vertical butts. This results in significant twist being introduced into the plate (Figure 14.59), and twist cannot be achieved by rolls.

Correctly applied, the number of different shell plates in the parallel body of a tanker or bulk carrier, can be as few as five. When this approach is applied to decks, bulkheads and tank tops, its impact can be a significant reduction in engineering, lofting and production man-hours. It also makes the use of special tooling cost effective and practical, as the extent of tooling will be small.

Another shell detail that involves extra work content is insert plates (Figure 14.60). This is because of the additional welding and chamfering of the insert plate. This can be eliminated by making the insert plate the full strake width, thus eliminating much of the additional welding. The chamfering can be eliminated by increasing the thickness of the plating surrounding the insert plate to that necessary to gradually build up to the required insert plating thickness in steps allowed by the classification society rules, without chamfering.

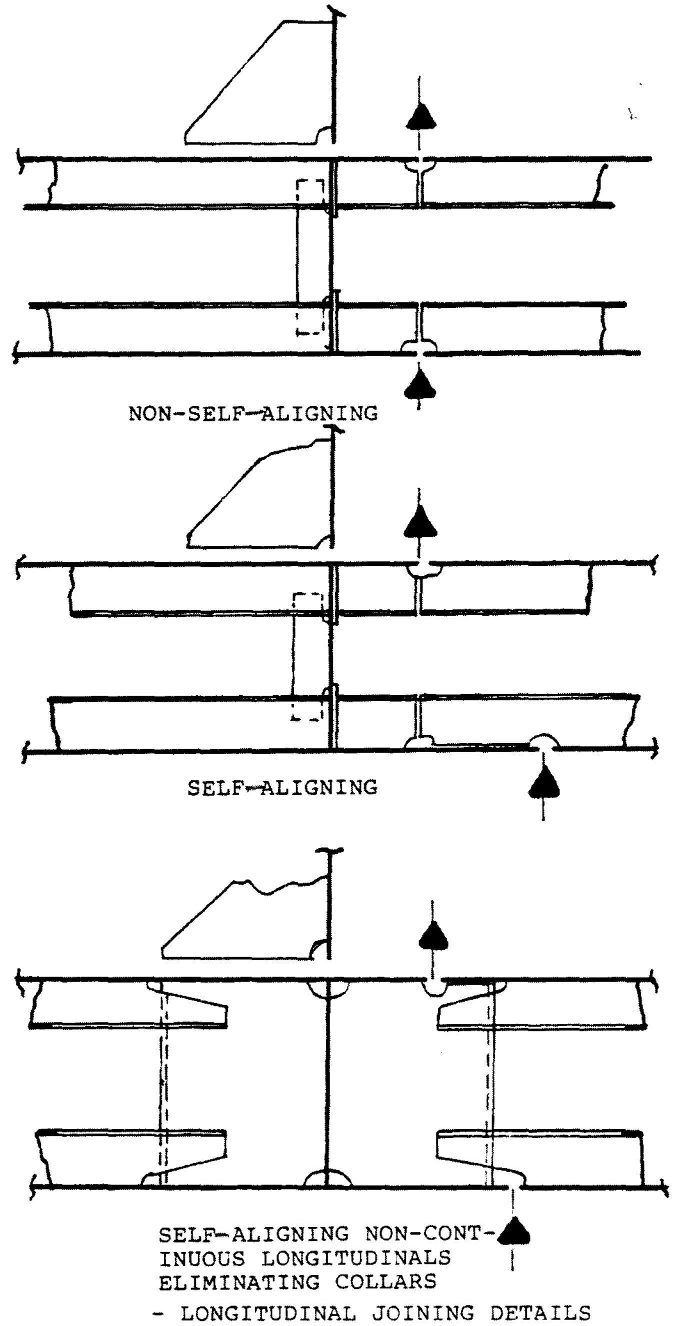


Figure 14.56 Block Break Connections in Way of Double Bottom Tanks

Many shell assemblies and/or blocks require plate or pin jigs to be able to construct them. This is an additional work content and by design it tan be eliminated. To do this it is necessary to either arrange flat structure, such as decks, flats and bulkheads, into the shell block so that they can be used as the assembly reference planes on which to set the internal structure and then attach the shell plates. Or else the internal web frames must be deliberately designed with their inner surfaces in a common plane for each block, in the

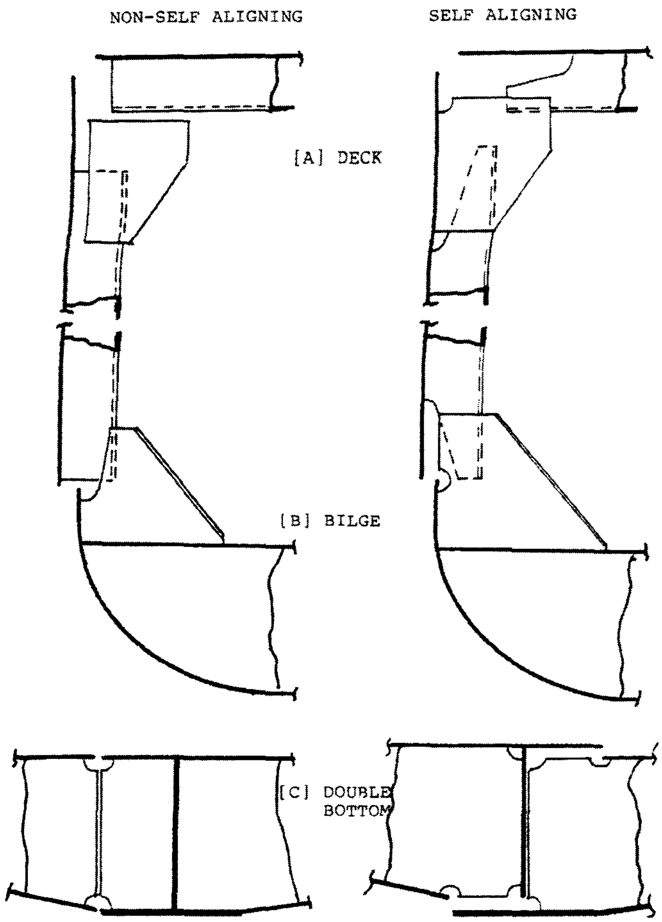


Figure 14.57 Block Break Alignment Considerations

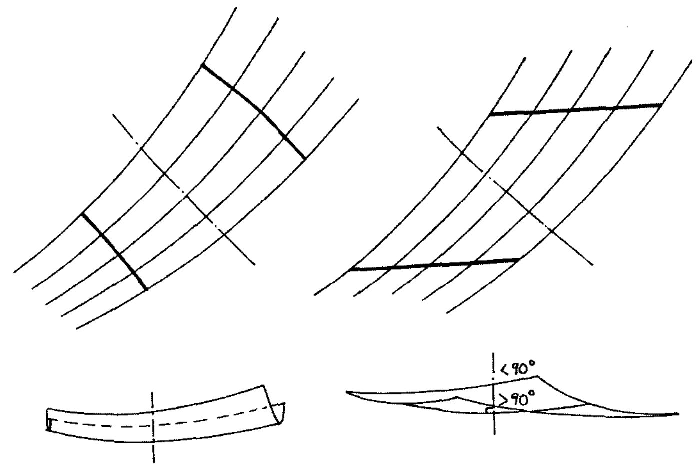


Figure 14.59 the Effect of Modern Shell Plate Straking

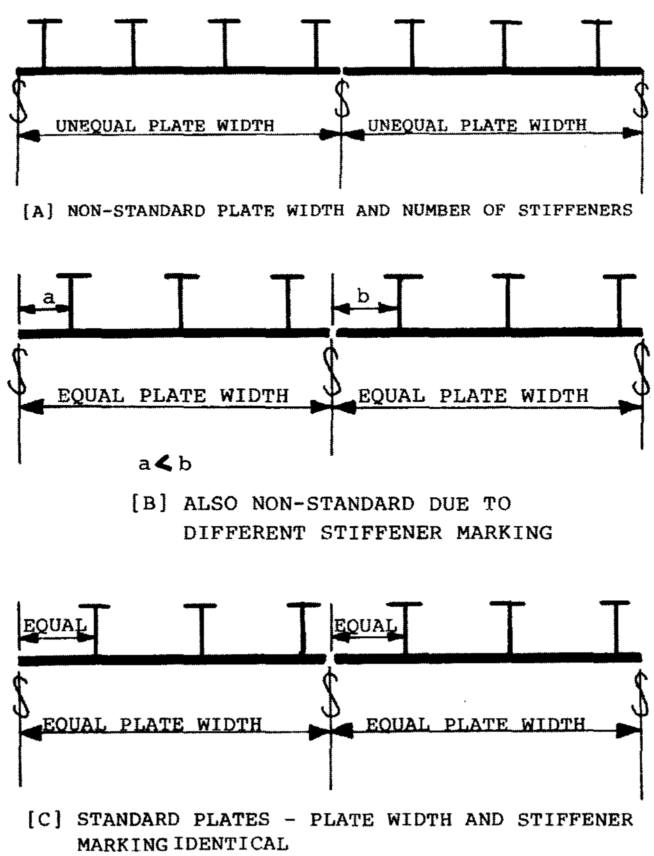


Figure 14.58 Standard and Non-standard Plates

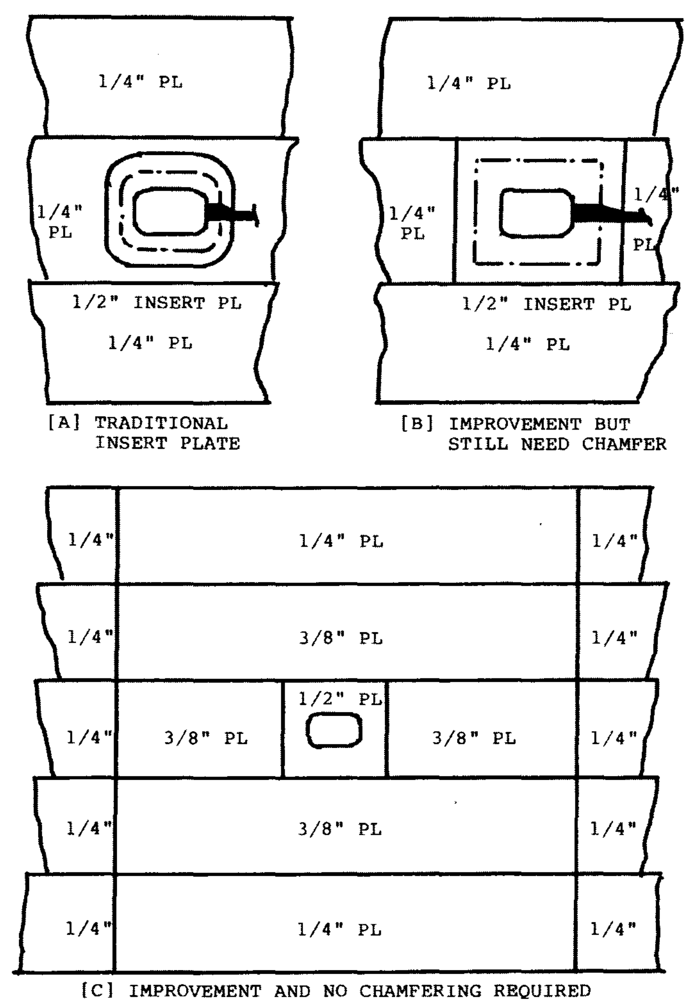


Figure 14.60 Shell Insert Plates DFP Considerations

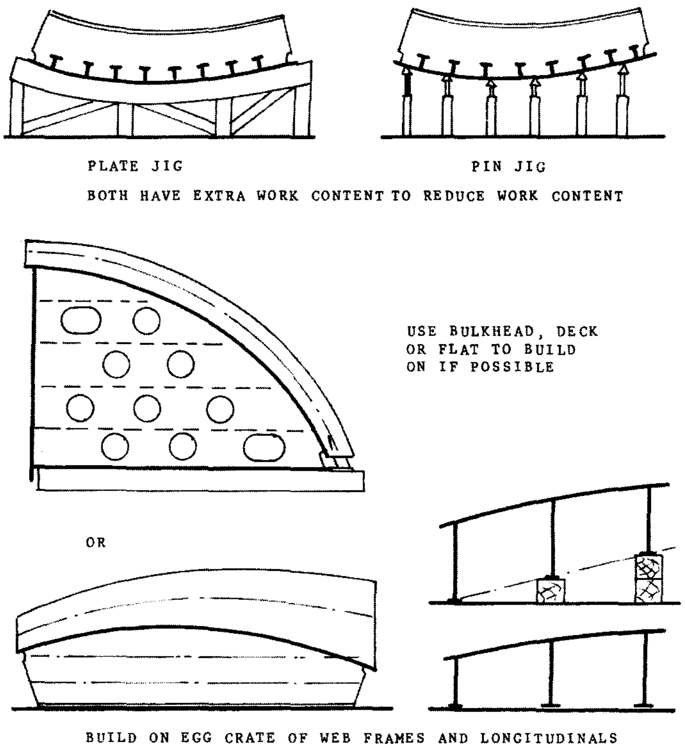


Figure 14.61 Curved Block Design for Production

same way that the upper surface and bevel angle of roll sets are used. These concepts are shown in Figure 14.61.

Cut-Outs The design of cut-outs for frames, longitudinals and stiffeners can also adversely influence work content, especially in naval work, where most of them at the shell must be chocked or collared. It is possible to eliminate cut-outs by slotting the floor, web or bulkhead, cutting away the flange of the frame, longitudinal or stiffener, and inserting a bracket to effectively maintain the sectional area of the frame, etc.

Comer cut-outs, snipes, drainage and air holes must take into account the construction methods and equipment that the shipyard intends to use. For example, if automatic 6r even gravity feed welders will be used, a detail allowing continuous fillet welding will be best, whereas for manual welding a complete edge cut detail may be better, especially if weld oil/water stops are combined in the detail.

The practice of making air holes smaller than drain holes in floors, girders, etc., is unnecessary and they should be made the same size.

Brackets There are many approaches to the design of brackets for frames, beams, longitudinals and stiffeners. In the days of the piece-by-piece erection of structural parts on the building berth, brackets were very simple. Even where shape was involved, they were fitted at the ship frame by frame. Figure 14.62 shows the evolution of some frame and beam brackets. Type (A) is a pre-computer aided lofting and NIC burning bracket. It was often sheared or burned from plate drop off or scrap and two standard sizes generally covered the complete ship. Standard II was used for shaped brackets and the excess material was simply cut off to suit each connection when joining frame to beam. Type (B) shows a bracket, which is practical only through the use of computer aided lofting and optical or NIC burning. As type (B) can be accurately cut, it can be used with advantage to align frame to beam and shell to deck. Type (C) is a bracket which utilizes the same concept as type (B) but attempts to eliminate the complex cutting of the ends of beams, frames, stiffeners, etc., required by type (B).

Its advantage is that as it is cut by N/C machine, all shaping can be easily accomplished and then the end cut on the frame, etc., becomes a simple straight cut. Its disadvantage is that as it is still used for alignment, it usually requires a larger bracket, thus encroaching on internal space. Another way to reduce the work content of brackets is to use thicker material and eliminate flanging or welding on a faceplate. This is allowed by classification rules.

Webframes Ships such as tankers and bulk carriers, and also some large naval ships, incorporate many web frames in their structural design. The usual design approach utilizes ring web frames with their many faceplates and web stiffeners. Figure 14.63 shows typical ring web frames and an alternative approach utilizing non-tight plate bulkheads in place of the ring web frames. The non-tight bulkhead web frame can be constructed for less man-hours than the usual ring web frame as it eliminates many differing parts including thick faceplates, which are often rolled to shape. It can also be constructed on a panel line with automatic and semi-automatic assembly equipment. However, in the case of coated spaces, the cost increase for the coating of the additional surface area must be taken into account. Where ring web frames must be used they should be simple in design without any curved inner contours or shaped faceplates (Figure 14.64). Also the faceplates should be located on one side of the web and not centered or even offset as a *tee.*

Access The location of access holes through the structure is important from the productivity point of view and must be considered for all positions of the assembly or block during construction and not only for the final ship attitude, as illustrated in Figure 14.65. It is a noticeable practice of many designers to center access holes in floors, girders, etc., making them difficult to use, and often requiring steps to be installed.

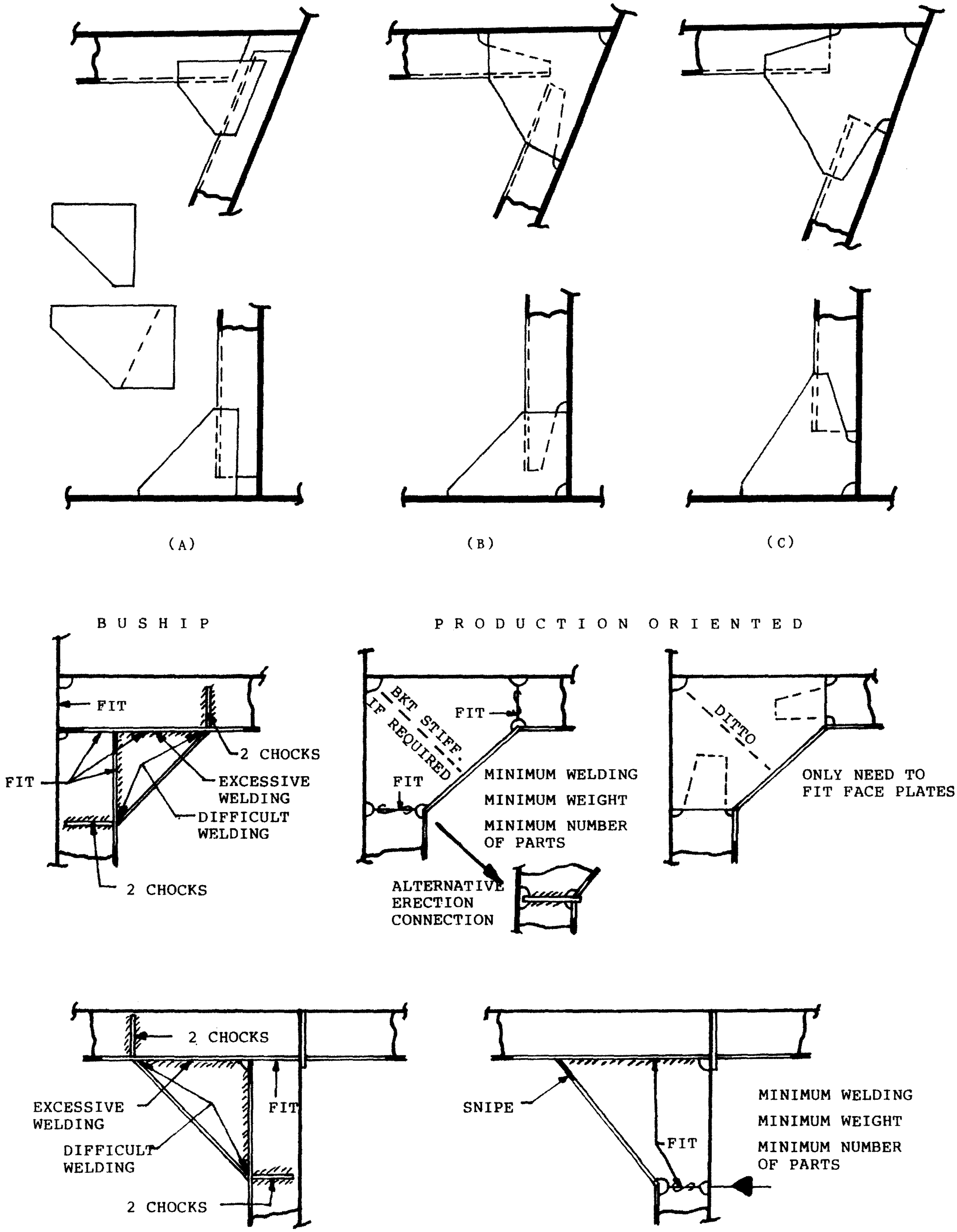


Figure 14.62 Typical Brackets

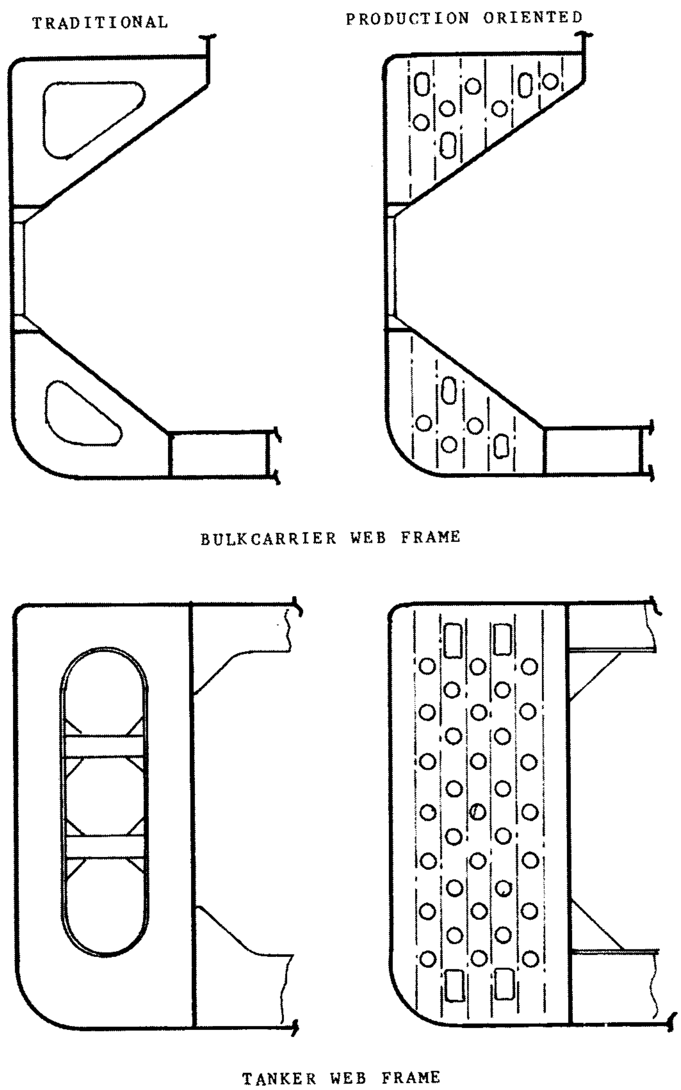


Figure 14.63 Web Frame Alternatives

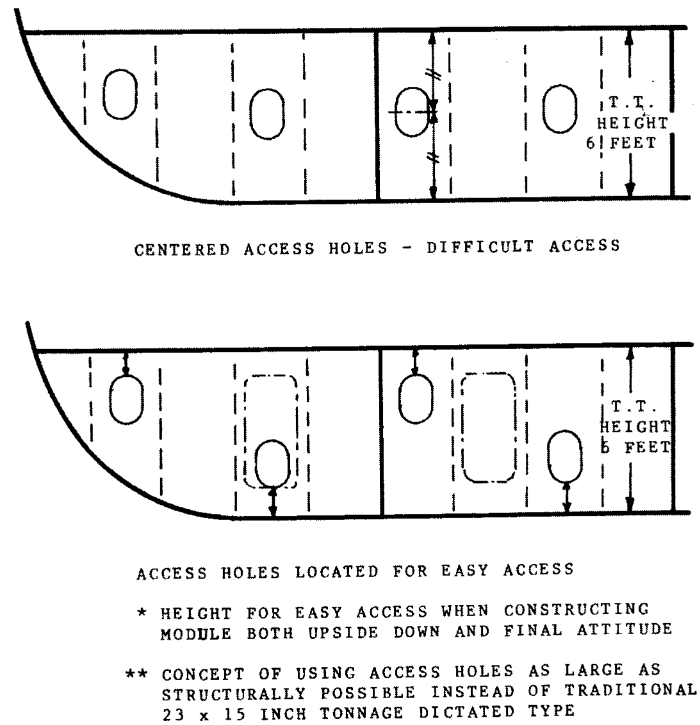
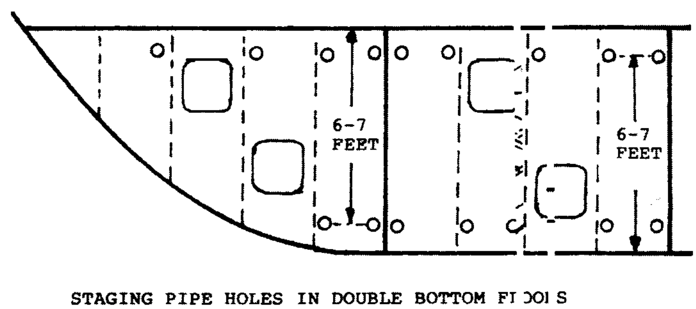
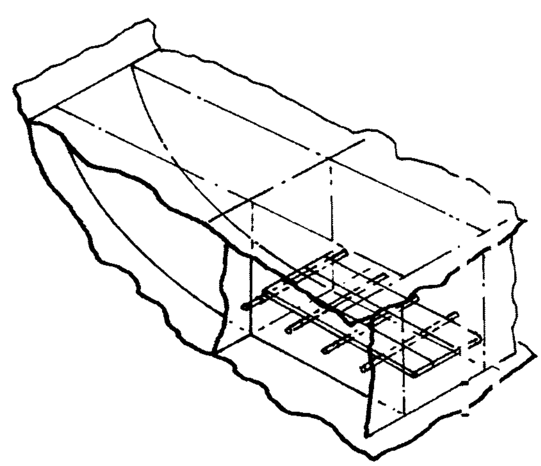


Figure 14.65 Location of Access Holes





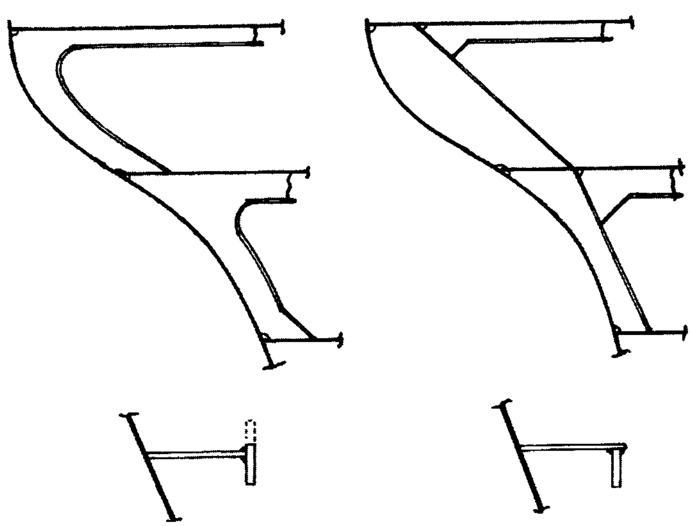


Figure 14.64 Web Frame DFP

Figure 14.66 Designed-in Staging System

During the construction and for maintaining the ship in service, staging is required in many spaces. Integrating the requirements into the design as permanent features can eliminate this. For example, for staging, 40 mm diameter holes can be cut in floors, girders, web frames, deck transverses, etc., thr6ugh which 35 mm diameter staging pipes can be placed and staging planks laid across the pipes as shown in Figure 14.66.

This concept was shown in reference (9), which also showed the cutting of hand and toe holes in the structure to assist access throughout the ship. These staging and access boles can be efficiently cut by the automatic burning machine when cutting the plate. Permanent *built-in construction and access galleries* are also a possible way to improve productivity through improved and safer access.

Penetrations One area of significant work content faced by shipbuilders of naval and other sophisticated ships, is the cutting of penetration holes for pipe, HVAC and electrical systems. This must obviously be done for systems when they pass through bulkheads, decks and external boundaries but it is usual practice to see it also for deck transverses, girders and web frames. The need to penetrate the latter items should either be eliminated or they should be made easier to penetrate. It can be eliminated by the design of minimum depth members and the running of all systems inside of the members or if the members cannot be made smaller, by increasing the tweendeck height or width of the space to allow the systems to be run inside of the usual sized members. Members should be designed to be easily penetrated by systems. That is, the depth of the member can be increased and the web material cut away in a standard pattern, to allow the systems to pass through. Penetrations through bulkheads can be arranged in an insert plate as shown in Figure 14.67.

Scantling Standardization/Number Reduction In a recent Contract Design for a small 75 meter naval service ship, the original Contract Design utilized 12 different thickness of plate and 51 different shapes. Although one of the worst examples ever seen, it is, unfortunately, quite common for designs to be prepared without any regard to keeping size differences to a minimum. The shipyard reduced those to 4 plate thicknesses and 9 shapes during detail design with less than a 1 percent increase in steel weight. However, the man-hour savings resulting from the-easier

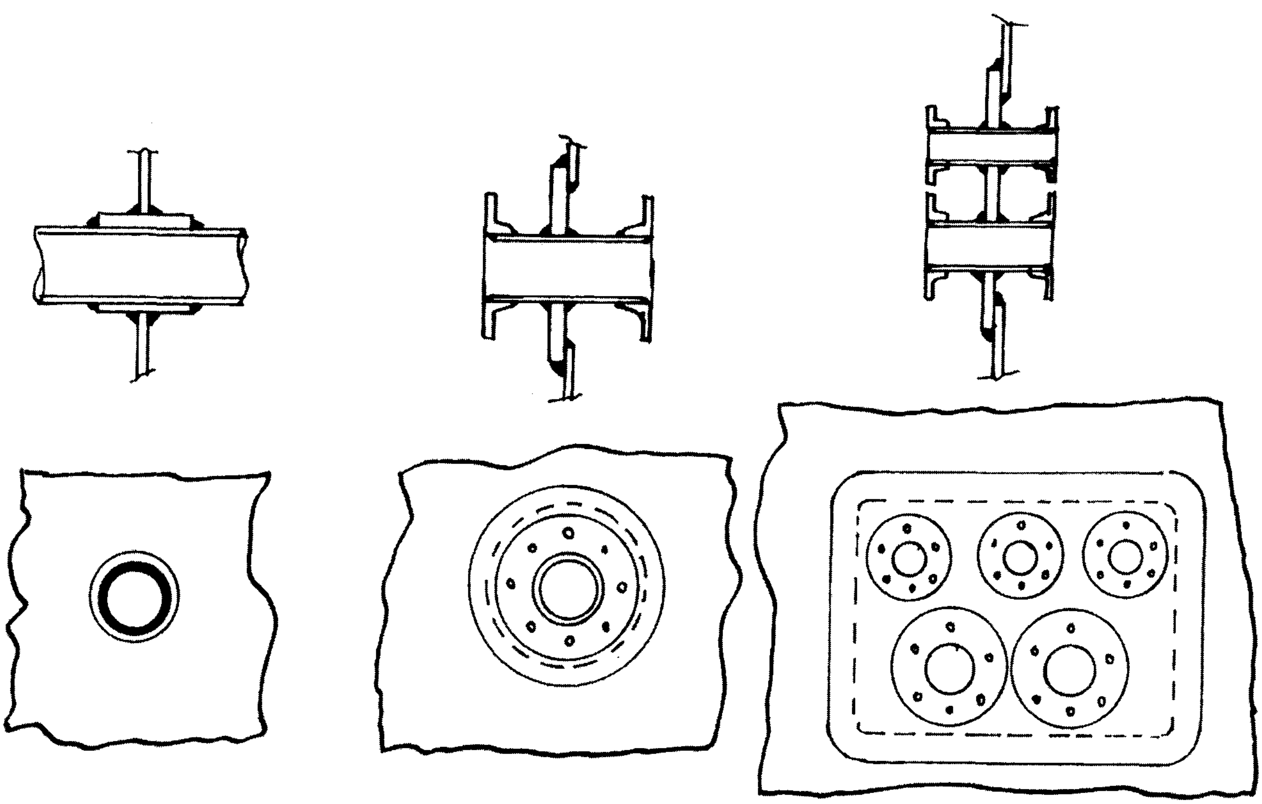


Figure 14.67 Pipe Penetration DFP Considerations

receiving, storing, handling, processing and installing was 6 percent of the steel construction budget.

Bilge Framing In a longitudinally framed ship, the longitudinals in way of the bilge radius are of high work content due to their shaping, twisting, closed angle fitting and cut-out collaring or chocking. The use of bilge brackets in place of the longitudinals is a productivity-improving alternative (Figure 14.68). Obviously, with computer aided lofting and NIC burning, the bilge brackets are easily produced. This approach also provides simpler and better control of the shape of the bilge shell plates. Obviously, before utilizing any of the structural details proposed, a complete producibility/cost benefit analysis should be performed by each shipyard to ensure that the selected detail is the best for their particular facility, equipment and methods.

14.3.4.2 Structural fittings

It is usual to group certain items which are either integrated into the structure, such as stem and stem frames, or connected to it, such as bitts, chocks, steel hatch covers, manholes, ladders and structural doors, into a category which is commonly known as Structural Fittings. Foundations are sometimes included in this category. Many of the items in this group were castings in the past and have been replaced by weldments, such as bitts, stems and stem frames.

There is considerable opportunity to apply design for production techniques to structural fittings. For example, when welded stem frames were first designed to replace castings, they were still designed as an independent item from the rest of the stem structure and many shipyards are still doing this. With modular construction there is no logic for this and the stem frame should be integrated into the stem block. This would significantly reduce the work content as the sternframe is effectively eliminated as a separate work item. The replacement of the stem casting by a weldment was already discussed, but it obviously requires the cooperation of the designer of the lines to be able to do so.

The traditional design of rudders results in high work content rudders. This can be reduced by simplifying the design through the following approaches:

- constant section throughout the depth,
- vertical leading and trailing edges,
- spade rudder instead of rudder supported by sole piece or horn, and
- horizontal bolting coupling instead of tapered stock and nut.

These concepts are shown in Figure 14.69.

Foundations for marine equipment are traditionally pedestal type made out of plate. They usually support only one piece of equipment. Even before advanced outfitting was developed, it was an obvious productivity advantage to integrate the foundations for multiple-associated equipment. The unitization, as it is called, of steering gears, hydraulic power plants, inert gas systems and purifier installations have been commonplace for some time. The use of standard foundations is obviously worthwhile due to reducing design, engineering and lofting effort and production fabrication and installation man-hours due to multiple runs and

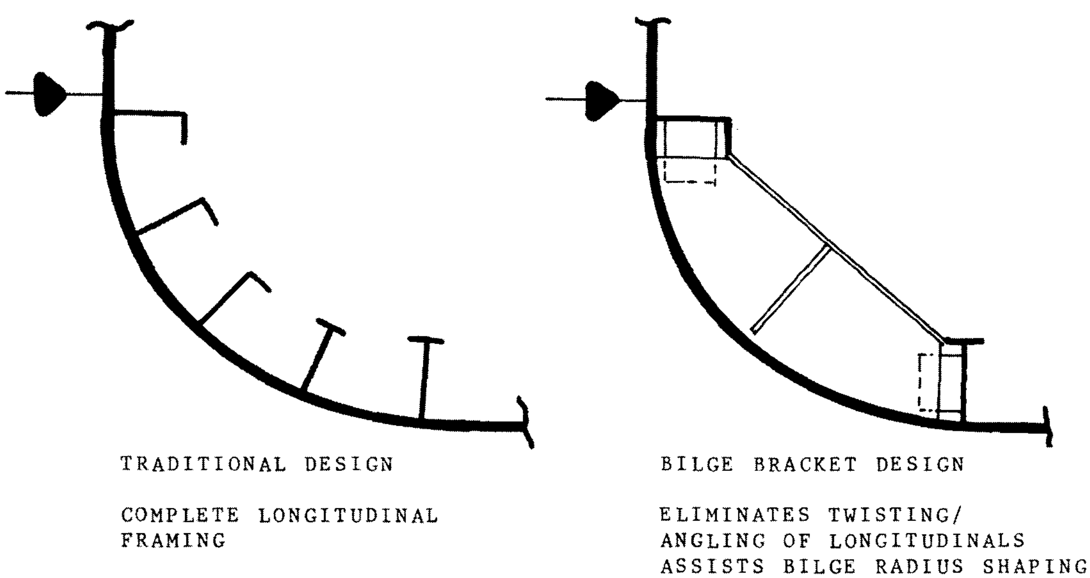


Figure 14.68 Bilge Framing Alternatives

work familiarization. Foundation design for production depends on shipyard equipment and worker capability, but, in general, the following approaches have provided low work content design (Figure 14.70):

- minimize number of parts,
- minimize number of unique parts,
- foundation designer and equipment arranger must work together. Sometimes moving the equipment a few inches can significantly simplify the foundation design and construction with no adverse impact on the arrangement design,
- do not mix plate and shapes, that is, make the foundation completely out of either all plate or all shapes,
- standardize on a few structural shapes, such as angle, channel or square tube,
- run supports vertical. Do not slope supports,
- provide any required *back up* structure on the same side as the foundation, that is, integrate it with the foundation,
- eliminate fitting joints, maximize lapping joints,
- use sheet metal independent drip pans in lieu of built-in,
- group a number of small items onto a common foundation, and
- securing bolts must be easily accessible. Otherwise, use studs.

For the remaining structural fittings, the use of standards is an essential design for production approach. It is illogical to redesign and/or redraw items such as hatch covers, railings, structural doors, ladders, flag and ensign staffs, etc. for each new design.

One item that is surprising in its lack of standardization in many shipyards is manholes and their covers (see example in subsection 14.3.6.4). For some reason the cover and gasketing for the coaming, raised and flush types are not made the same. There is no reason why this should be so. It is the different parts of each type that should be designed to suit the standard cover and gasket. Obviously, not all of the possible structural fittings have been covered, but the intent should be clear from those that were.

14.3.4.3 Hull outfit

Hull outfit covers joiner work, insulation, furniture, habitability equipment, deck covering and painting. In some shipyards, it also covers deck machinery, hull piping and HVAC. The two latter items will be discussed separately in the following sections on PIPING and HVAC, respectively.

The major item of recent development in hull outfit that is in keeping with design for production is modular accommodation-units. The advantages of modular accommodation-units are, not surprisingly, similar to those for advanced outfitting units, namely:

- relocation of work from ship to shop, resulting in easier access, efficient material handling, cleaner and safer environment,

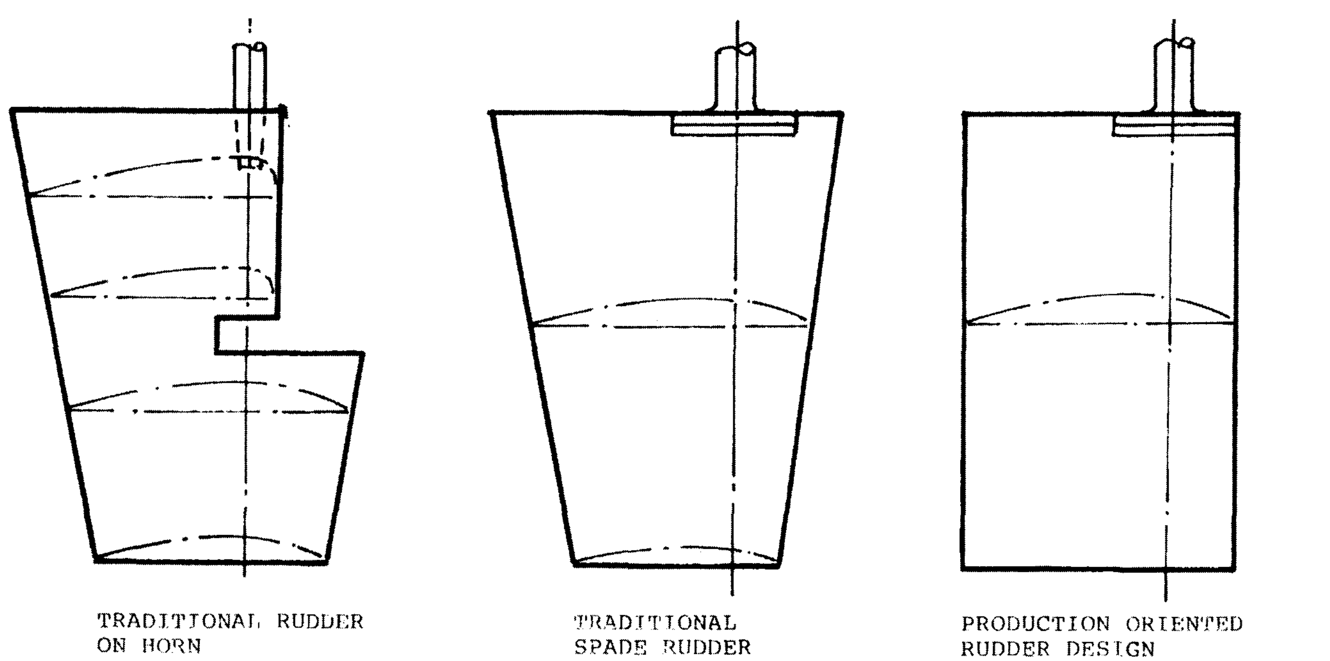


Figure 14.69 DFP for Rudders

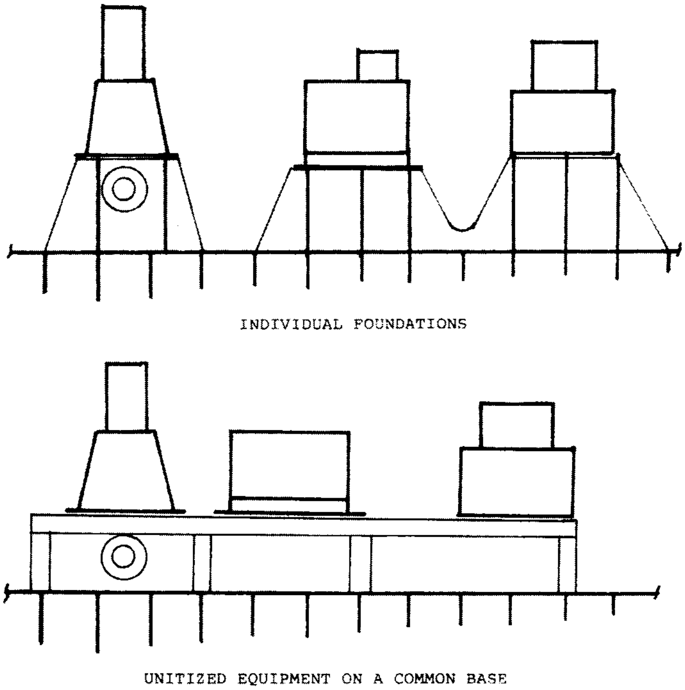


Figure 14.70 DFP for Foundations

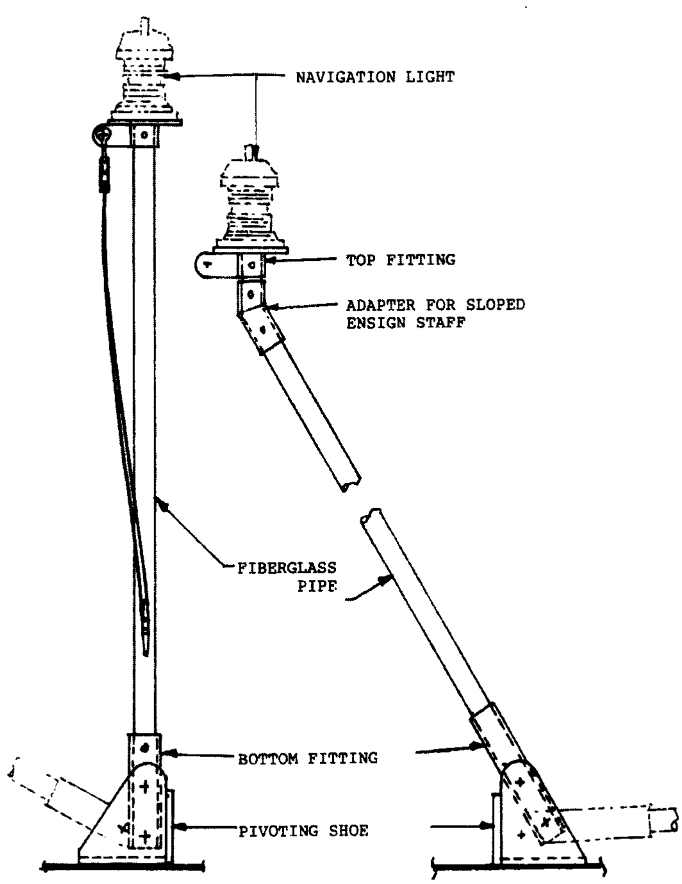


Figure 14.71 Standard Flag Staffs

- possibility of assembly line techniques for multiple units,
- elimination of transporting many small items to ship,
- simpler material control, \
- reduction in material scrap,
- shorter installation time onboard the ship,

Again, standardization is an essential design for production approach, not only for individual items but also for units such as modular toilets, modular furniture, complete cabins, galleys and storerooms.

A number of design for production ideas for hull outfit are (Figure 14.71 through 14.76):

- incorporate foundations for deck machinery into the equipment design and weld direct to the structure,
- use above deck slide or *A frame* anchor davit instead of hawse pipes (Figure 14.76),
- use modular accommodatiOn-umits. If not complete cabin units at least modular toilets, modular furniture and common outfitted joiner bulkheads,
- keep furniture off the deck. Support by joiner bulkheads, as this will eliminate sub-bases and their fitting to the deck,
- use modular galley equipment/walls,
- use carpet over bare steel in cabins,
- use trowelled in place deck covering in passageways, and
- use non-grinding terrazzo in galley and toilets.

Another idea that results in significant work content reduction, is to apply hull insulation to joiner linings and ceil-

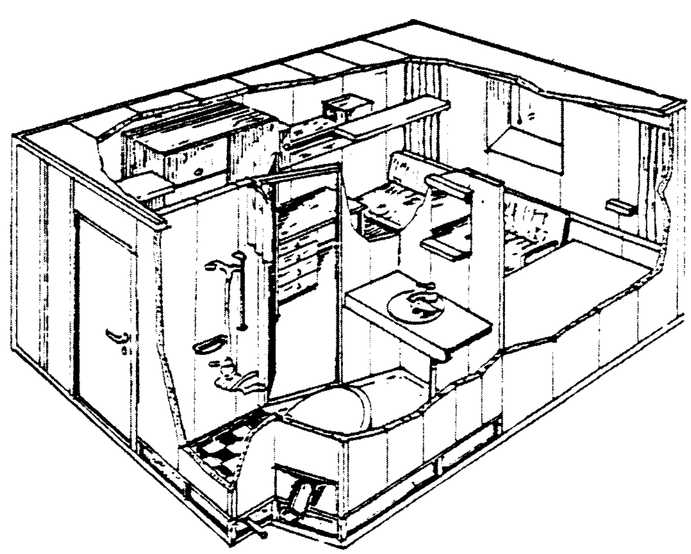


Figure 14.72 Accommodation Cabin Module

ing instead of the inside surfaces of hull and deckhouse structure. This eliminates work effort for fitting insulation between and around frames and beams as well as cutting flaps for welded supports for vent ducts, piping and wireways. Many of the currently available modular accommodation systems use this approach, but it can be and was used by a shipyard in Sunderland, England in 1964 for traditional joiner lining and ceiling installations. As previously mentioned in discussing arrangements, service spaces should be provided adjacent to each toilet, laundry and other service locker, which can be accessed by easy removal of joiner lininglbulkhead panels.

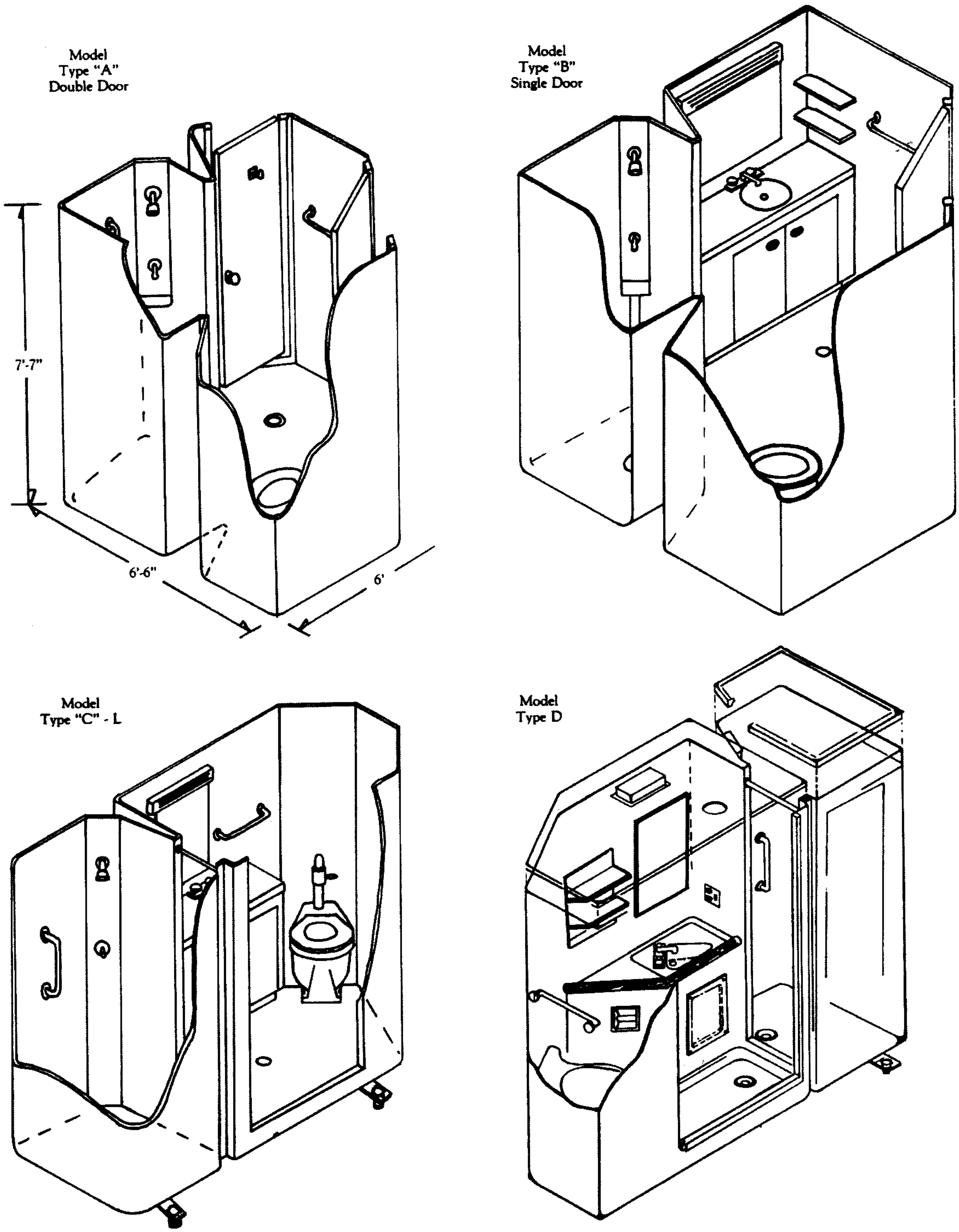


Figure 14.73 Toilet Modules

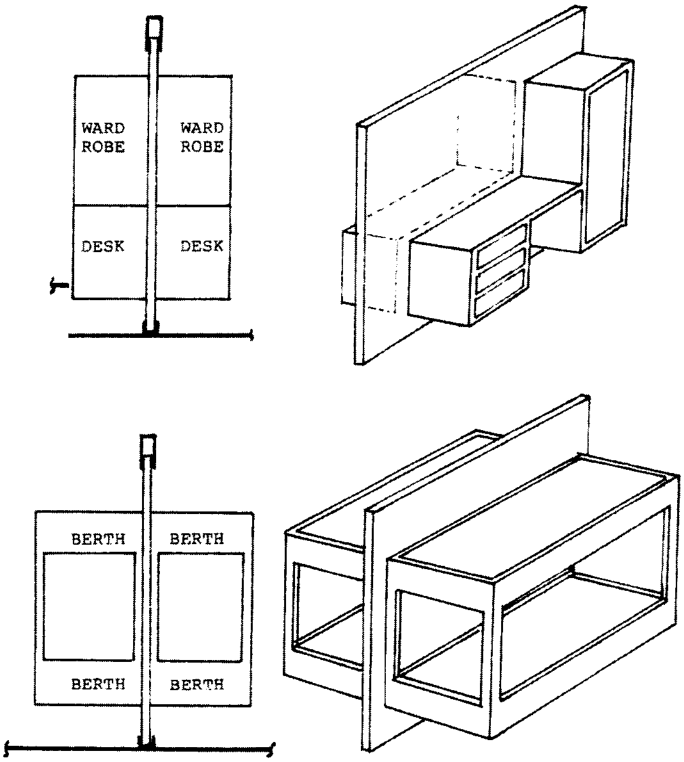


Figure 14.74 Furniture Bulkheads

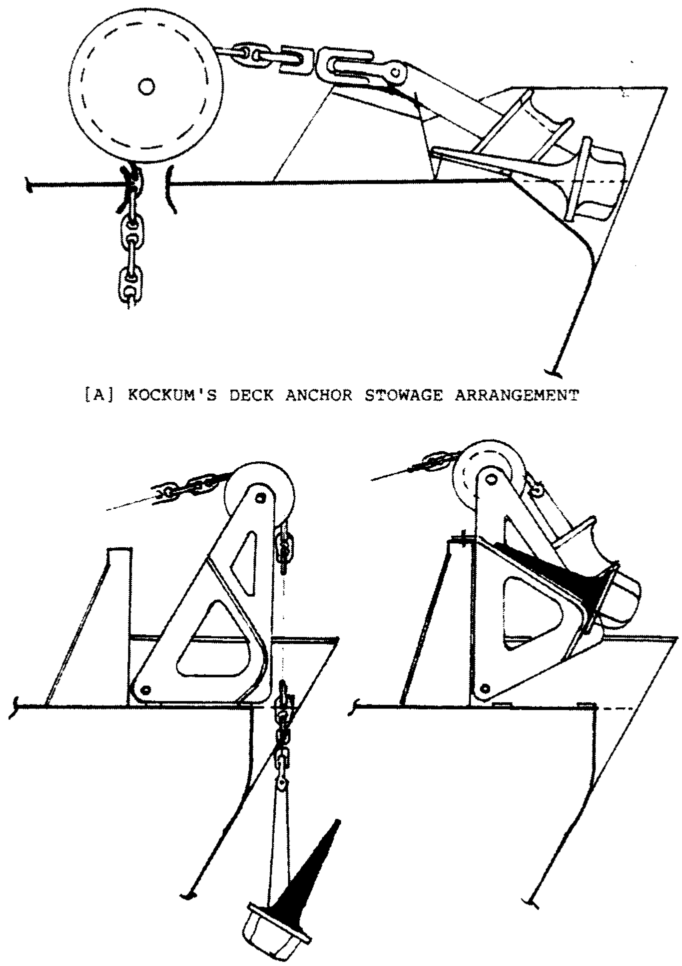


Figure 14.75 DFP Anchor Stowage

14.3.3.4 Machinery

Very few shipyards today design and manufacture the propulsion and auxiliary machinery, which will be installed in the ships that they build. They will probably purchase the machinery from other manufacturers who specialize in the manufacture of the different machinery items. Therefore, the machinery design group is usually responsible for designing an integrated power plant from many *stock* or *standard* items of equipment available from many different suppliers. They may also be responsible for the design of the machinery space ventilation, gratings/floor plates and ladders.

The design of the machinery installation can significantly assist the ultimate goal of improved productivity by standardization. For example, foundations for propulsion and auxiliary machinery could be standardized for the equipment and different ship structural arrangements designed to suit the standard foundations. Some years ago, Det Norske Veritas attempted to standardize the arrangement of machinery spaces for different ship types. The idea was that all equipment associated with a given function or system should be grouped together and located in the same area for similar ship types. The idea is still a good one as it allows the familiarization of both shipbuilders and ship crews of similar machinery plants for different ships. By utilizing such an approach and assigning vertical and horizontal system routing corridors for the different systems, such as piping, ventilation and electrical wireways, the task of other engineering groups and production can be significantly simplified and reduced. Again, standardizing the system routing corridors can save considerable engineering and production man-hours.

Assembly and block breaks must be carefully developed between the machinery and hull groups to ensure that no major equipment or their foundations extend over the breaks as this will prevent installation of the equipment into the blocks before erection and joining.

Machinery Arrangement Even with the recent trend to unattended engine rooms and complete automation, ship machinery plants will still have maintenance and overhaul work performed on it regularly throughout its life. While machinery manufacturers have applied much thought during design, for easy maintenance of their equipment, it often

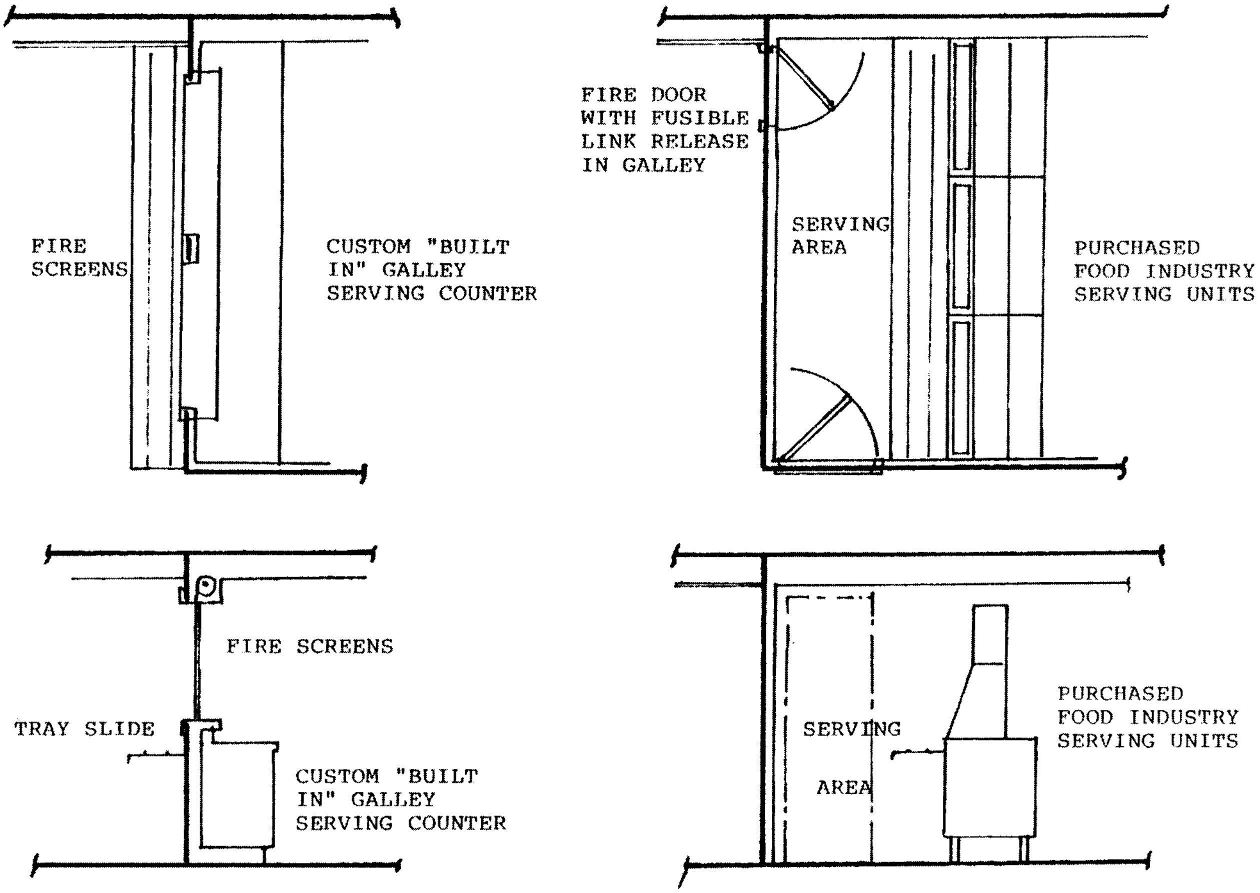


Figure 14.76 Galley Arrangement Concept

seems that little thought is given by the ship designer in the arranging of the machinery. The recent introduction and application of Human Factors Engineering if applied correctly should change this. During Contract Design, efficient transport routes for spare parts and tools must be developed along with good working space for required equipment withdrawal and maintenance, lifting capability, stores and spares locations, etc. Floor plate level and the level of the machinery space flat/s should be determined to be the most efficient for maintenance work, without compromising normal operational requirements. The arrangement of machinery, equipment and systems should be designed for easy cleaning. With reduced engine room crews, less time is available for this function, which is normally very difficult due to the dirt which accumulates when fuel, oil and water mix. Proper design of drip trays under equipment and of draining and collection system for same can assist in accomplishing this goal.

The lifting and transportation of equipment and spare parts should be considered for all machinery and large equipment, not just the propulsion engine and gear. The manual chain hoist is still needed in most machinery spaces of cur-

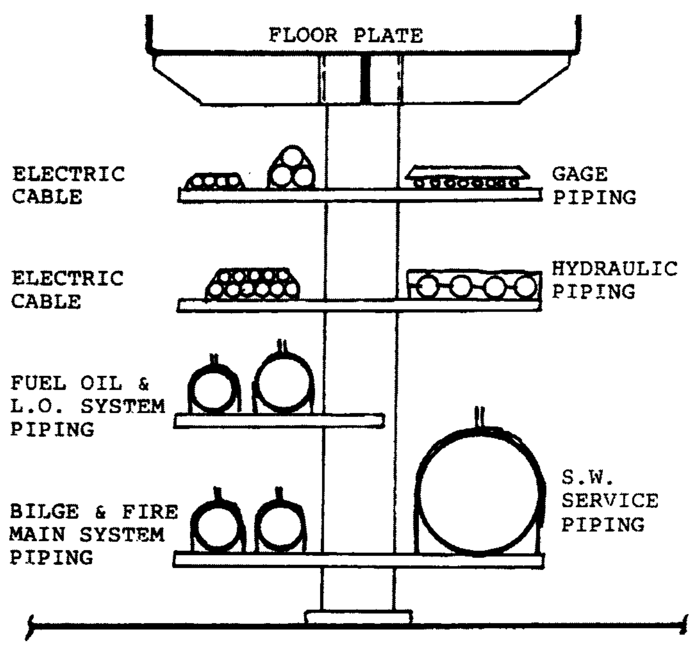


Figure 14.77 Integrated Support Concepts

rent ships. With small engine room crews this is no longer acceptable.

The location of spare parts should be an integrated part of the machinery arrangement design process and not simply left to whatever space can be found when the ship is nearing completion. When designing the supporting distribution systems, a balance must be maintained between minimum equipment and multiple uses and the design, which would be best for operations and maintainability. Design for production should not be applied to the detriment of design for efficient operation and maintenance.

The machinery arrangement development obviously must take into account whether or not advanced outfitting is to be utilized. The equipment association list, the network and the final diagrammatic are the basis for the design of an advanced outfitting machinery unit. The arrangement of the equipment and the overall dimensions of the unit will be affected by the space available in the machinery space and the other equipment or units therein. It is, therefore, normal for the design of the unit and the arranging of the machinery space to be performed concurrently. Units should be arranged with the following points in mind:

- identical units for identical major equipment should be located identically (True Modularity),
- units should be located with both the major equipment and the system storage tanks in mind so as to provide both the best operational and least cost arrangement,
- completely forget the traditional concept of mounting equipment on bulkheads, unless all the unit equipment will be installed as a unit onto the bulkhead. The design of a unit must be developed from the concept of support from only one plane. Occasional braces can be allowed for high small plan area units,

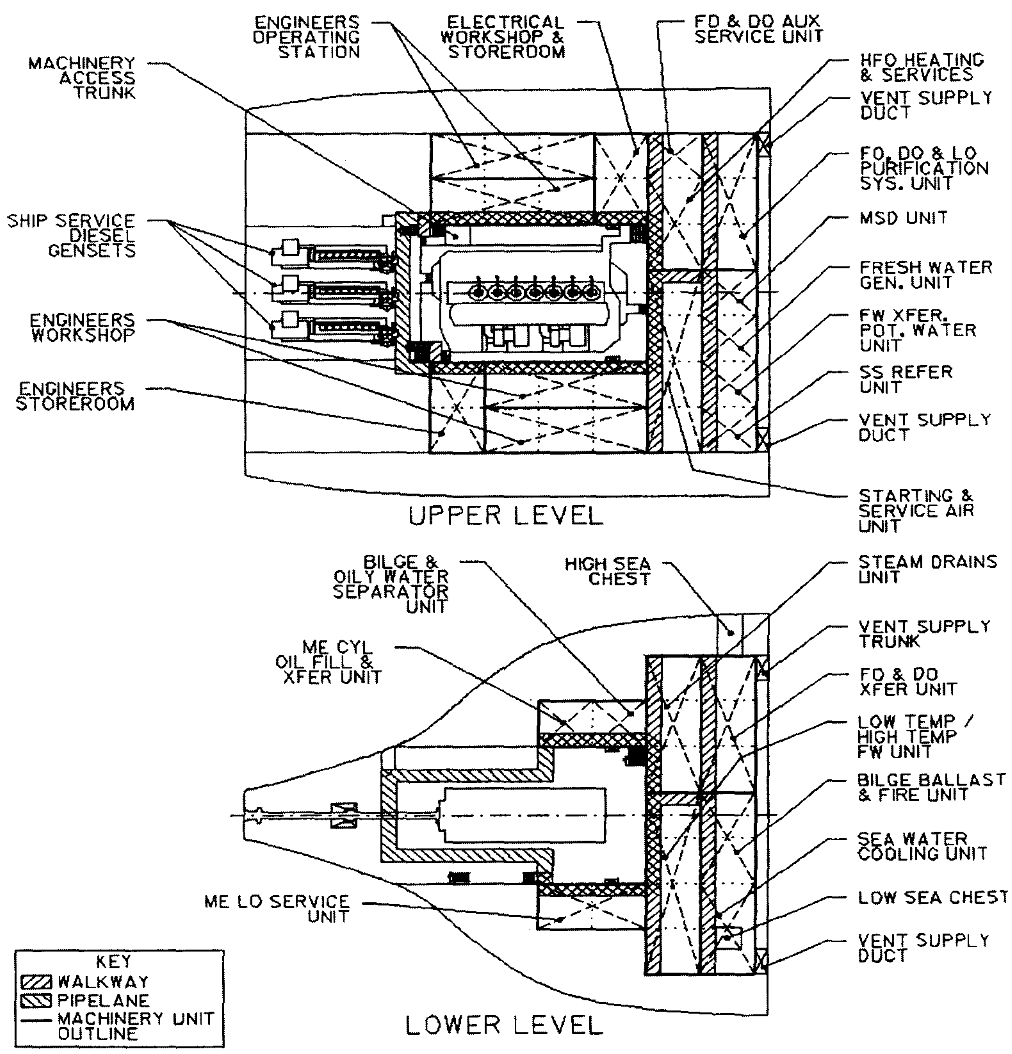


Figure 14.78 Space Allocation

- units should be arranged so that all piping runs are as short as possible and only in the transverse and longitudinal directions. Diagonal runs should be avoided unless absolutely necessary to suit unit design,
- in conjunction with the arranging of units, distribution system corridors should be established. Where possible major routing corridors should be integrated with floor plates, gratings, walkways and their supports,
- personnel access systems (floor plates, gratings, etc.) should only be that required to provide access to equipment for necessary service functions such as normal and emergency operation and maintenance,
- maintenance lifting or pulling arrangements should be fully considered when designing the arrangement and incorporated into the unit where practical,
- handrails should be arranged for safe access and protection, both during construction and after installation of the unit in the ship,
- combine as many systems as possible into a unit with good design and producibility in mind. For example, if large vent ducts are in the vicinity, attempt to combine them with walkways (Figure 14.77), and
- valves should be located so as to come up at the side of the floor plates and grating, and not below or through the middle of the floor plates.

Space Allocation The selection of the locations for all equipment, appurtenances and systems should be performed in a logical and formal way. This is true for all parts of a ship but is essential for machinery spaces. An aid to this process is the analysis of existing ships to determine space requirements for the various machinery, equipment, distribution corridors, etc.

Major independent machinery and standard auxiliary machinery units can be represented by the circumscribing block. To this can be added the surrounding space necessary for access, operation and maintenance. Such space should be designated as to whether it is inviolate. Then these can be used to develop a functional machinery space layout. Such a layout is conceptually shown in Figure 14.78 taken from reference 47. It is important to logically design the distribution corridors and not just provide space for them. When the corridors for different systems such as vent, pipe and wireways must cross each other, the concept of how this will be done must be developed.

TABLE 14.II Equipment Association List

SYSTEM
Propulsion Diesel Engine L. 0. Service
MAJOR EQUIPMENT
Propulsion Diesel Engine
ASSOCIATED EQUIPMENT
L. 0. Standby/Prelube Pump
L.0. Filter
L.0. Cooler
L.0. Duplex Strainer
Rocker L. 0. System Tank
Rocker L. 0. Standby Pump

Equipment Grouping Even before the concept of advanced outfitting it was good design practice to prepare an equipment association list for any major piece of equipment to be arranged and installed in a ship. This association list was used for a number of purposes, such as checking vendors supplied unattached equipment. However, for the purpose in mind, it was and should be used to develop location in the system of all the items and the connections between them. Equipment, which requires a foundation, can also be noted. The addition of valves, gages, switches, etc., is accomplished when preparing the diagrammatic. The equipment association list was then used to develop a connection network, which became the basis for the system diagrammatic. For advanced outfitting *On- Unit* construction, it is necessary to use the equipment association list and the connection network to select the best grouping of the equipment on the unit. A typical equipment association list is shown in Table 14.11.Figure 14.79 is the resulting network. Figure 14.80 shows a typical design diagrammatic prepared without any consideration of equipment association grouping. It is easy to see the illogical location of the equipment. Figure 14.81 shows the same diagrammatic developed from an equipment association network.

Floor Plates One area where many shipyards spend an inordinate amount of effort is in the installation of machinery space floor plates. This is usually because they are designed independently of other systems and always seem to have much interference. To avoid this they end up being custom-fitted onboard the ship. The application of advanced outfitting *On-unit* approach will eliminate much of this problem as can proper design sequence when advanced outfitting is not used. Notwithstanding the many bad experiences with floor plates, it is possible to successfully design and install a standard floor plate system (Figure 14.82). It is beneficial to keep the area alongside the propulsion machinery clear of systems so as to eliminate the possibility of foundation/system interferences.

This also provides a maintenance work area and by incorporating hinged floor plates, maintenance and access to the machinery is improved. The practice of designing machinery space handrail stanchions of pipe as well as the rails should be discouraged and the simpler *hull type* flat bar stanchions should be used instead.

14.3.3.5 Piping

The design of piping systems for a Contract design usually only consists of unsized diagrammatics for propulsion and operational essential systems. Like all other systems, standardization will assist in accomplishing design for production. Not only standard components but standard complete systems, such as shown in Figure 14.83, and standard Touting corridors. Again, whether or not advanced outfitting will be utilized, the steps outlined in the section on Machinery Arrangement should be followed and expanded, namely:

- prepare equipment association lists,
- prepare equipment connection networks,
- prepare system diagrammatics, and
- prepare routing diagrammatics.

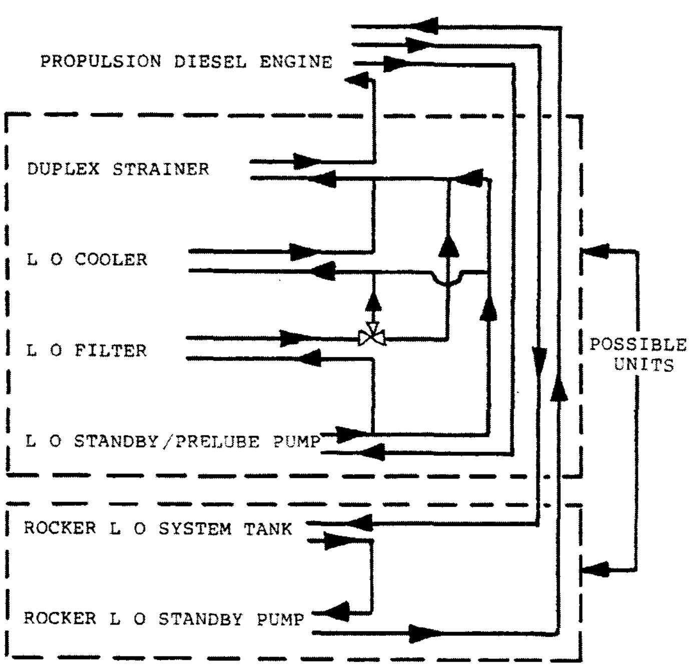


Figure 14.79 Equipment Connection Network

14.3.3.6 HVAC

In traditional design and construction of ships, systems such as piping, HVAC and electrical are always *fighting* each other for space. To overcome this problem some designers allocate space priorities to different systems such as HVAC first, large piping next and electrical wireways last. Unfortunately, from experience it is known that this approach does not work well. This traditional conflict does not end with design and engineering. It continues out in the shops and on the ship during construction. Added to this shipboard conflict caused by design, is the *field run pipe* and *who gets there first* problems. However, these problems can be changed into planned integration of systems by applying the approach described herein.

An essential step to ensure production friendly design of HVAC systems is to plan the distribution corridors early in the design development at the same time as the corridors for the other systems. Again, the use of standards for HVAC components and diagrarnmatics is an effective DFP approach. Obviously, the standards should be minimum work content designs. By correctly planning the design of HVAC systems

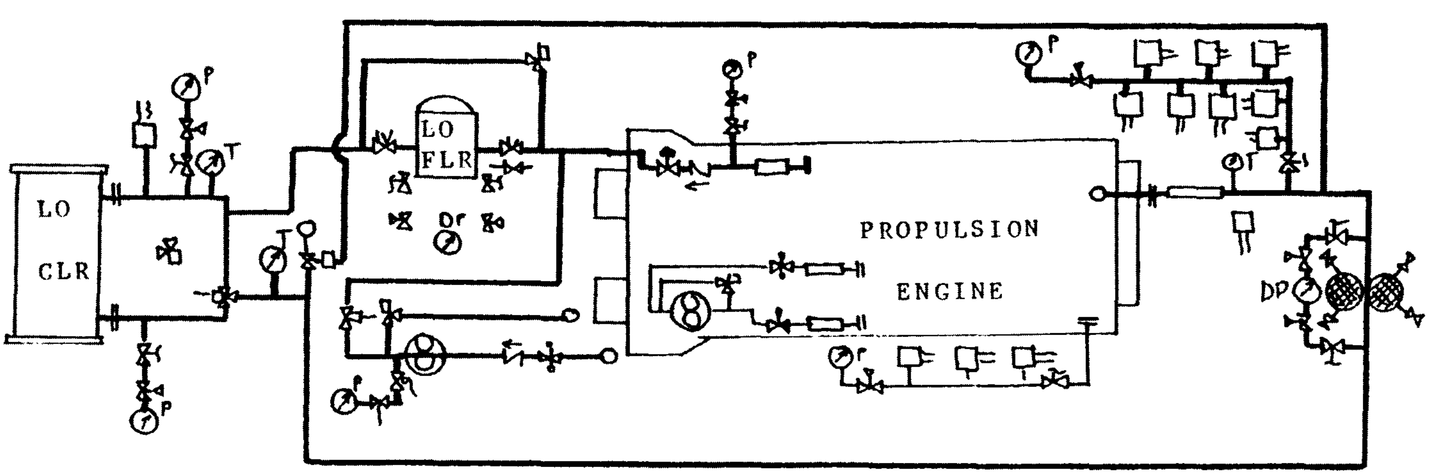


Figure 14.80 Illogical System Diagrammatic

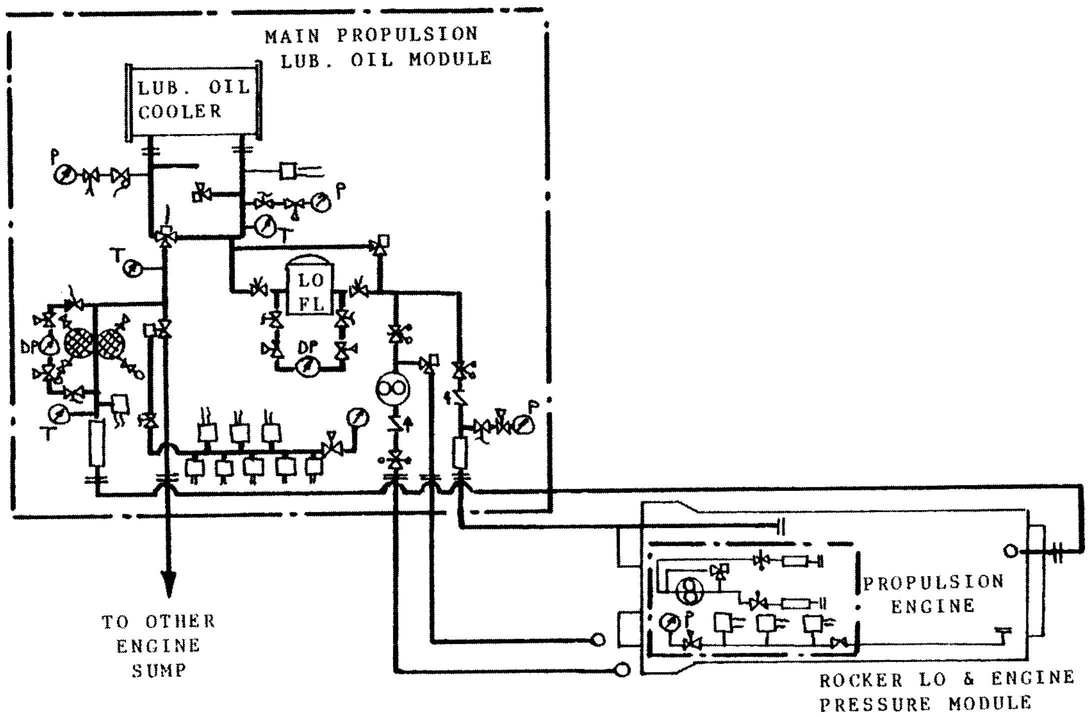


Figure 14.81 Logical System Diagrammatic

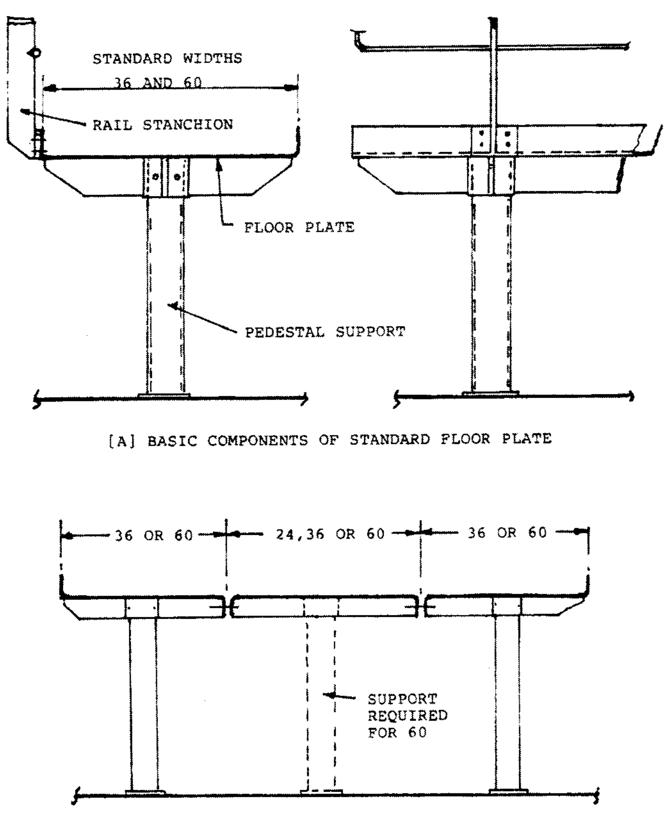


Figure 14.82 Standard Floor Plate System

during Basic Design the need for high work content penetrations, duct jogging and section changes can be eliminated. By considering louvers and plenum chambers as integral parts of the structure instead of HVAC fittings, considerable design and construction man-hours can be saved. The use of high-pressure ventilation systems will reduce the size of the ducting and can result in worthwhile installation man-hour savings. However, the cost of any special noise attenuation treatment could cancel the savings out. The use of individual room convector heater/cooler and even hotel type through the wall units should be examined as a potential productivity improver without any operational disadvantages. Again, the above ideas must be considered during the preparation ofthe Contract Specifications to ensure that they can be utilized if found of benefit to a shipyard.

14.3.3.7 Electrical

As for the other traditional disciplines, the first design for production requirement for electrical systems is that they be considered along with and integrated with the other systems. This integration of all systems is essential if an efficient and easily constructed ship is to be designed. Routing corridors for wireways should be assigned during Basic Design and used for cable routing as the design is developed.

Marine electrical design and engineering is the ship dis-

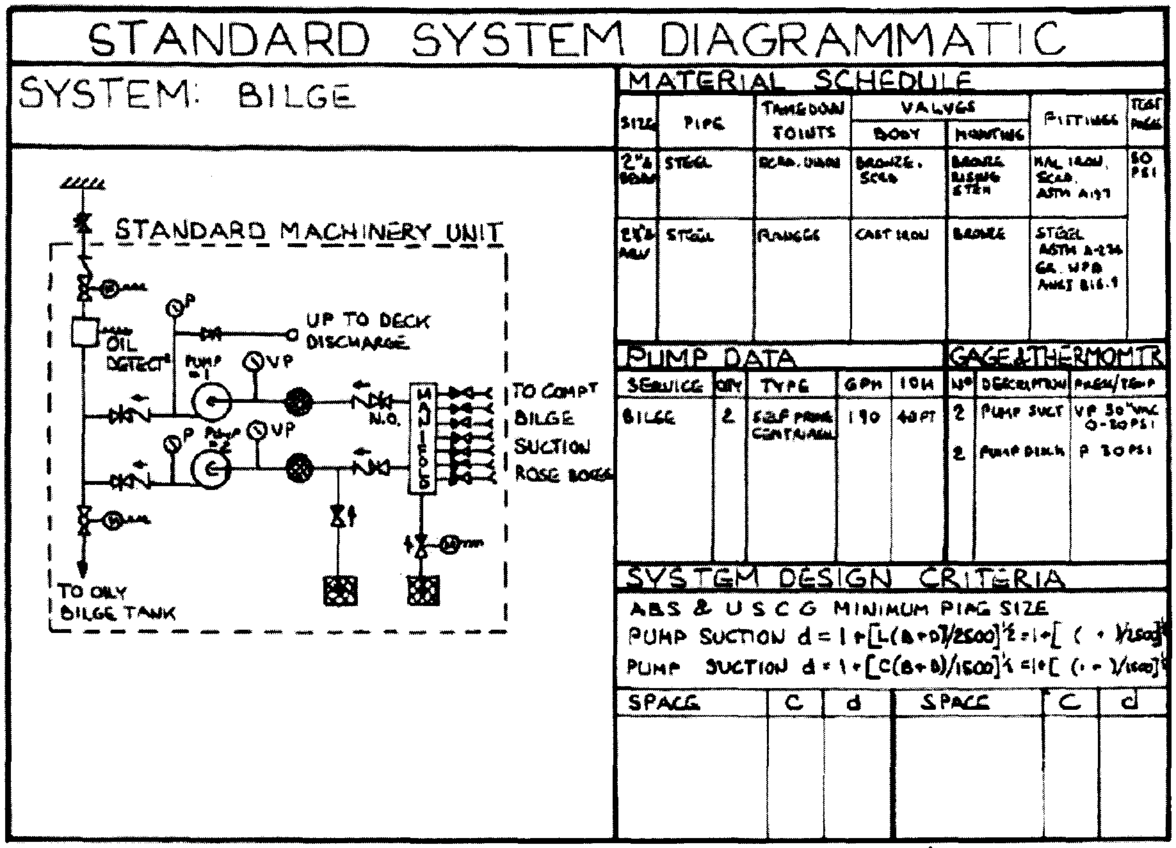


Figure 14.83 Standard System Diagrammatic

cipline that has had the least effort expended to improve it. The design for production potential is therefore large and it should be targeted for significant development. The impact of advanced outfitting and zone construction is substantial on traditional marine electrical design but can be used to guide the required electrical design for production development. Aspects such as combined control panels for units, On-block and zone electrical installation; erection of completed deckhouses, etc., must be considered and, again allowed for in the design approach and the Contract Specifications. Typical electrical DFP concepts are shown in Figure 14.84

14.3.3.8 Integration of systems

Everyone knows that the most cost and operationally efficient ship is one in which all its components are well integrated. Many also know that the integration of the many systems also offers work content reductions. Therefore, the deliberate efforts to integrate the ship systems during dezsign are an essential part of design for ship production. The approach is not new. It is just that the traditional engineering specialization/organization divides responsibility for individual systems in the same part of a ship to many groups. Also the preoccupation with independent system design and current approach to working schedules apparently prevents many designers from attempting integrated design.

The integration of systems for advanced outfitting units is simply a micro application of the approach compared to the macro application for the complete machinery space or the entire ship. The specialization of skills in both engineering and production relies on the ability of managers to ensure that the design and construction of individual systems result in an integrated final product.

It is obvious that there is a basic design need to ensure that all parts of a product are efficiently integrated and that the many compromises that are necessary during design are the best.

It is still possible today to see machinery spaces where individual pipe runs have obviously been designed and installed independently of all other pipe runs. Further, no attempt will have been made to integrate the pipe hangers with each system being independently *hangered* to the ship's primary structure. The foundations for the equipment will be individual and floor plate and vent duct supports will also be independent. When surrounded by this inefficient application of material and production effort, it is easy to see the additional cost and weight and why it takes so long to build.

Advanced outfitting necessitates integration of systems to obtain full benefits. An innovative but practical attitude is required to successfully integrate the systems and a major tool to assist this is a Distributive System Routing Composite Drawing incorporating the assigned system corridors.

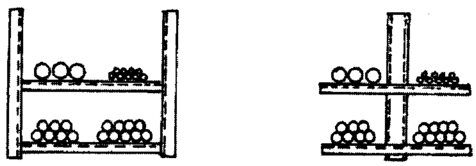


FIGURE 1.119 Typical hangers.

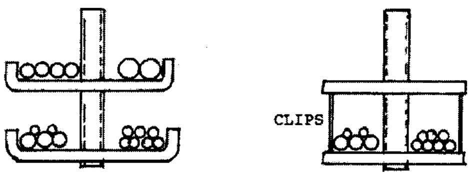
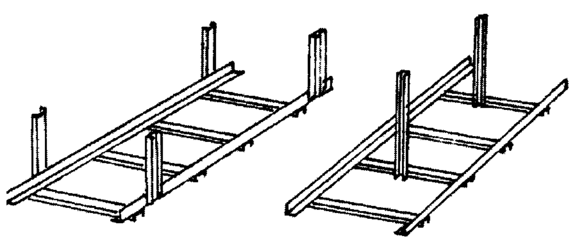
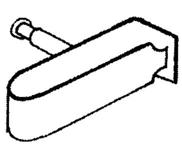
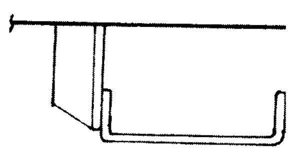


FIGURE 1.120 Cable-retaining methods.

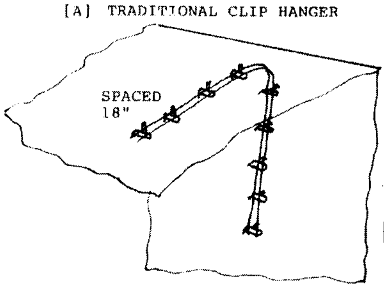


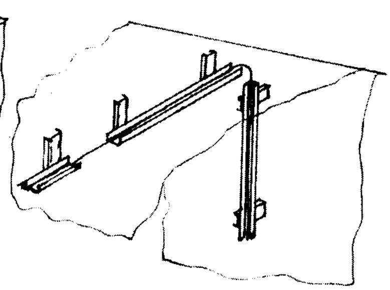


[A] TRADITIONAL CLIP HANGER

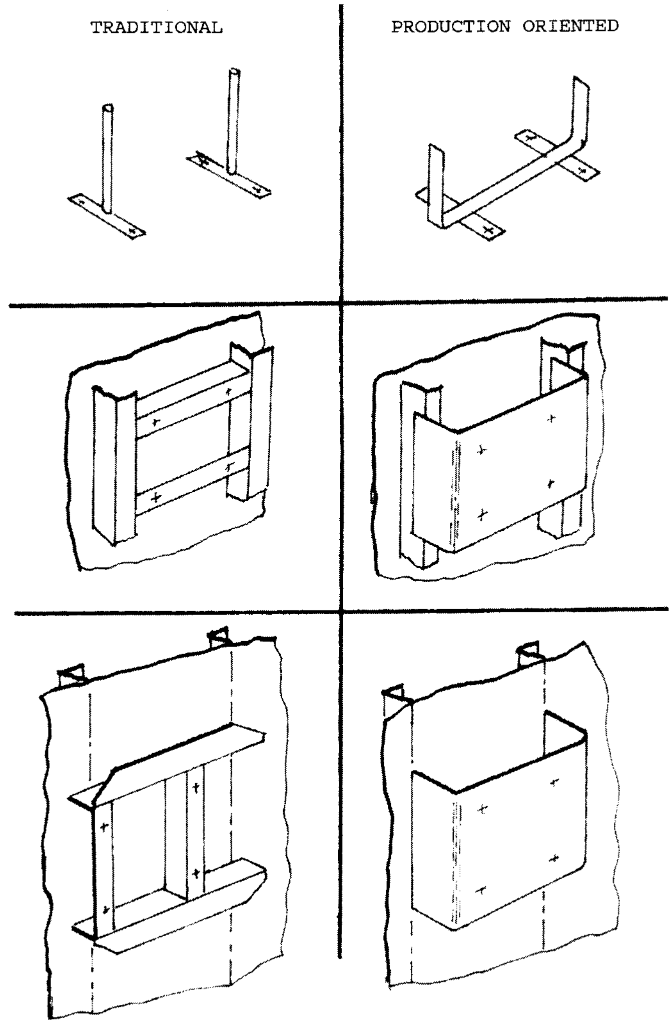


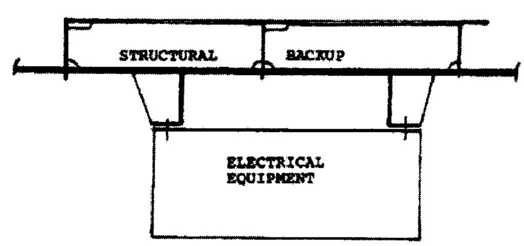
[B] PREFERED CHANNEL HANGER



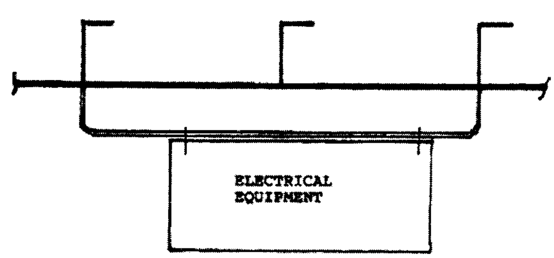


SUPPORTS SPACED TO SUIT BEAM/
FRAME/LONGITUDINAL SPACING





TYPICAL ELECTRICAL FOUNDATION WITH BACKUP



FLANGED PLATE FOUNDATION ELIMINATING NEED FOR BACKUP

Figure 14.84 Typical DFP for Electrical

14.3.4 Application Examples of DFP

To assist in the application of DFP a number of examples are presented. They range from the use of simple comparisons to the use of sophisticated computer-based decision-making tools.

14.3.4.1 Part reduction

The first example considers part variation reduction. Figure 14.85 shows a typical midship section for a product tanker. It has 2110ngitudinals on the shell, side longitudinal and centerline bulkheads. As the section modulus of each longitudinal depends on the head above it to the tank overflow, each longitudinal could be different in size. To reduce the number of different parts ship designers have grouped to 21 longitudinals into 4 to 5 groups of the same size. As the longitudinals in a group have to all be sized based on the lowest longitudinal in the group there is a small weight increase, but any additional material cost is insignificant compared to the man-hour savings resulting from the part reduction.

Another solution would be to make all the longitudnals the same size as the lowermost one, vary the longitudinal spacing and increase the plate thickness so that the global and local structural requirements were met. This would have a significant weight increase associated with it but this is moving in the direction of the longitudinal less ship or advanced hull structural design (48).

14.3.4.2 Block breaks

This example shows how the type of framing impacts the decision On-block breaks. Figure 14.86 shows how in a longitudinally framed ship, it would be better to have long blocks, whereas for a transversely framed ship wide blocks would be better. This is because the above choices would eliminate section joints and leave only plate joints.

14.3.4.3 Tranvsverse versus longitudinal framing

This example examines whether man-hour savings cam be achieved by changing from longitudinal to transverse framing on normal commercial ships such as container, tanker, bulk carrier, etc., by focusing on the double bottom as shown in Figure 14.87. The dimensions of the double bottom block are:

Length	12 800 mm
Breadth	12 000 mm
Depth	2000 mm
Frame spacing	800 mm
Longitudinal spacing	800 mm

(Note this will give 12 longitudinals rather than the 7 shown in the sketch.)

Table 14.m shows the comparison and that transverse

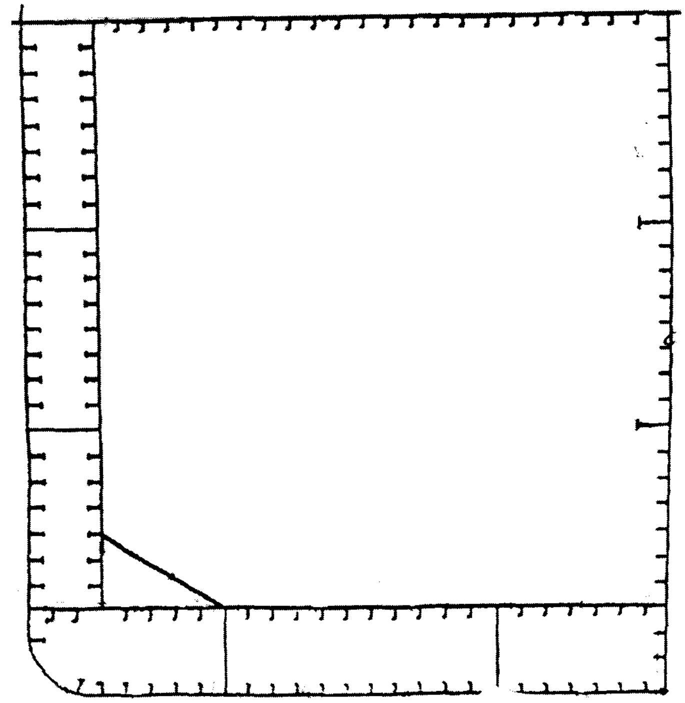


Figure 14.85 Product Tanker Midship Section

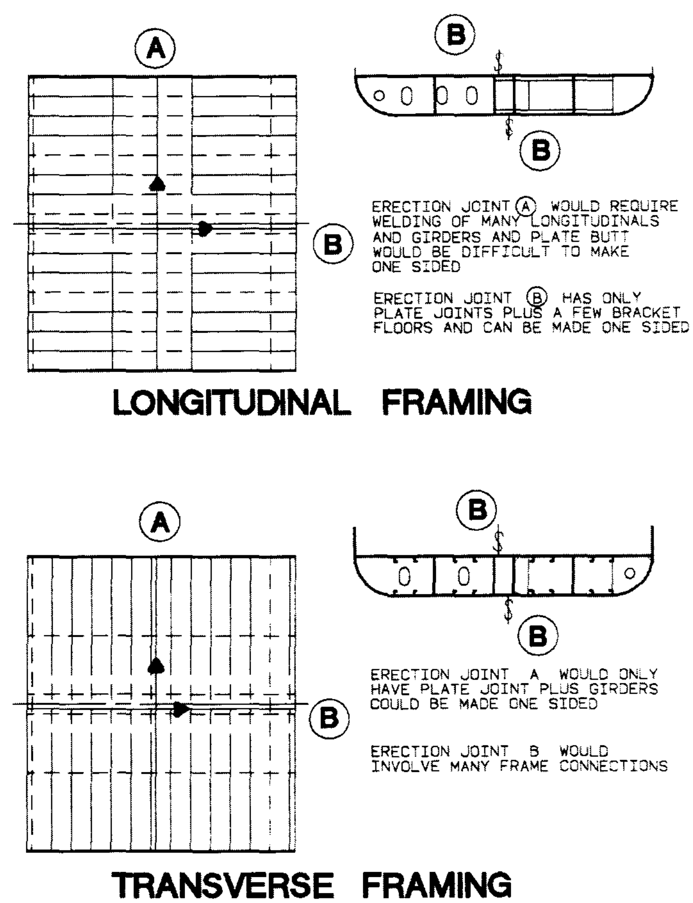
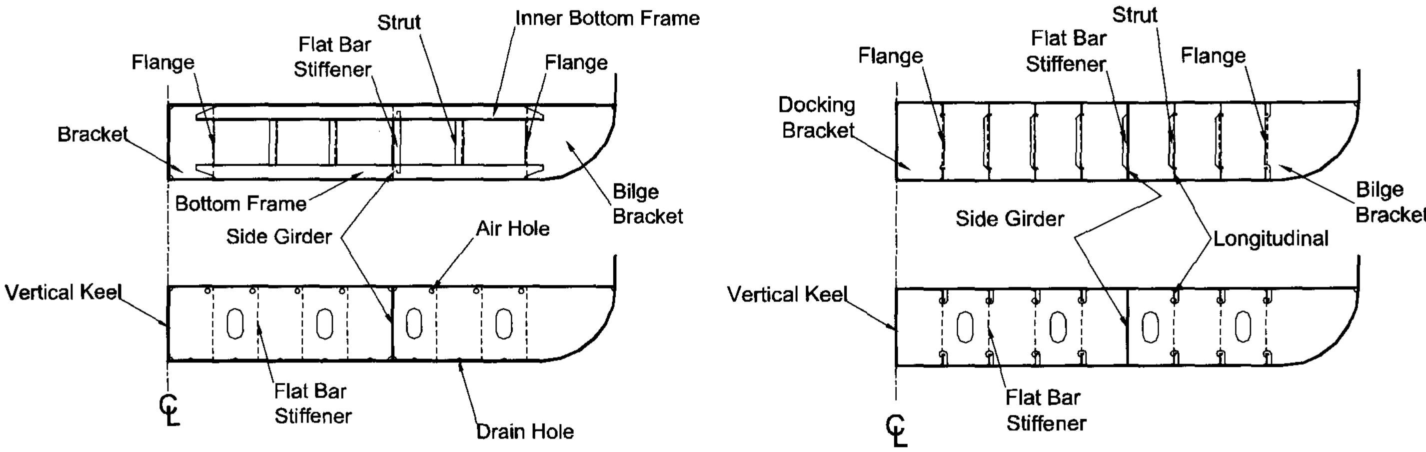


Figure 14.86 Block Break DFP



a) Transverse Framing b) Longitudinal Framing

Figure 14.87 Transverse Versus Longitudinal Framing in Double Bottom

framing can reduce the number of parts by 40%, the number of unique parts by 31% and the joint weld length by 17%.

14.3.4.4 Man hole cover

Many shipyards have standard parts and Figure 14.88a shows one shipyard's standard for man hole covers. It can be seen from the figure that the actual cover is different for each man hole type. Figure 14.88b shows the DFP solution to standardize the actual cover.

14.3.4.5 Slits and notches with chocks

This example uses the computer-based simulation to evaluate alternative designs for double bottom floor longitudinal/floor intersections by deriving the outcomes.

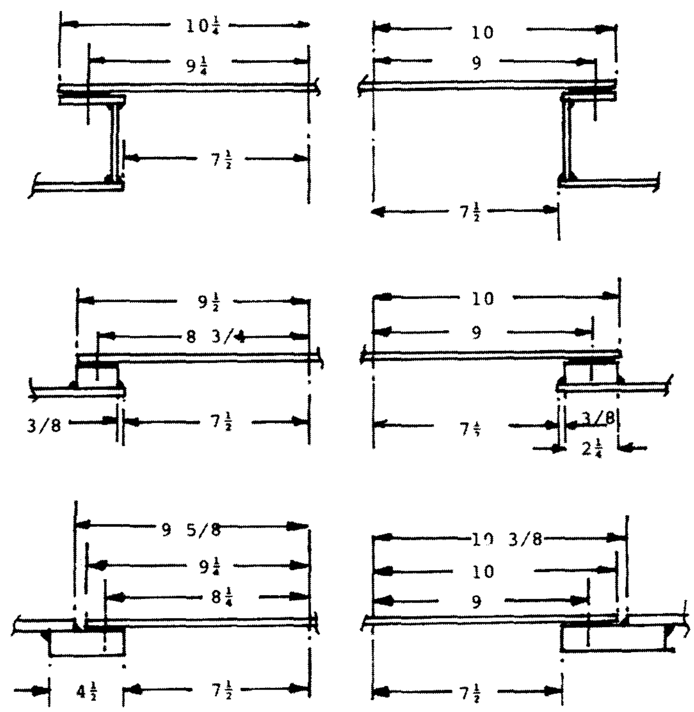
Computer-based simulation systems such as DELMIA, can be used to model the product, processes and resources for both cases and run to determine the cycle time and man-hours for each case, and the outcomes can be compared.

A double bottom structure for a container ship is used as an example. It consists of two stiffened plate assemblies; tanktop and the bottom, and eight subassemblies; 3 floors and 5 girders. Two different longitudinal notch shapes are considered, as shown in Figure 14.89.

Case I longitudinal notch shape design has several advantages and disadvantages over the Case II design, such as:

Advantages

- collar plates are not required resulting in less number of parts
- less welding length especially for the chocks that are difficult to access, and
- less cutting length.s



a) Original Standard Design b) DFP Standard Design

Figure 14.88 Standard Man Hole Design

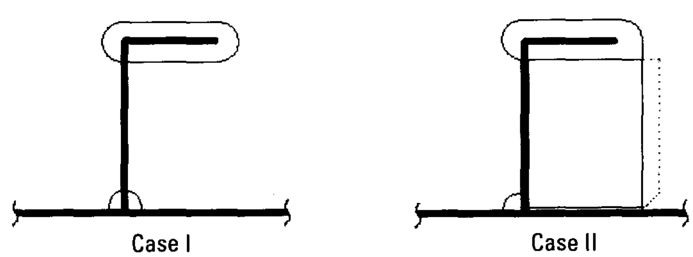


Figure 14.89 Two Longitudinal Connections

TABLE 14.III Tranvsverse versus Longitudinal Framing

	NOP	*NOUP*	*JWL m*	*WELD PROCESS*
TRANSVERSE FRAMING				
Plate Floor	3	1	168	Panel
Plate Floor Stiffeners	24	1	77	Subassembly
Bulkhead Floor	1	1	56	Panel
Bulkhead Floor Stiffener	12	1	39	Subassembly
Docking Bracket	12	1	86	Manual
Docking Bracket Stiffener	12	1	38	Subassembly
Bilge Bracket	12	1	120	Manual
Bilge Bracket Stiffener	12	1	38	Subassembly
Inner Bottom Frame	12	1	216	Panel
Shell Frame	12	1	216	Panel
Girder Stiffener	12	1	48	Subassembly
Weld Frames to Brackets	—	—	82	Manual
TOTALS	**124**	**11**	**1184**	**—**
LONGITUDINAL FRAMING				
Plate Floor	3	1	168	Panel
Plate Floor Stiffeners	36	1	115	Subassembly
Bulkhead Floor	1	1	56	Panel
Bulkhead Floor Stiffener	12	1	39	Subassembly
Docking Bracket	12	1	86	Manual
Docking Bracket Stiffener	12	1	38	Subassembly
Bilge Bracket	12	1	120	Manual
Bilge Bracket Stiffener	12	1	38	Subassembly
Inner Bottom Longitudinals	12	1	307	Panel
Shell Longitudinals	12	1	307	Panel
Girder Stiffener	12	1	48	Subassembly
Girder Stiffener Brackets	24	1	38	Manual
Inner Bottom Longitudinal Collars	24	2	19	Manual
Shell Longitudinal Collars	24	2	19	Manual
Longitudinal Connection to Floors	—	—	29	Manual
TOTALS	**208**	**16**	**1427**	**—**
Compared to Longitudinal Framing Difference	84	5	243	17%

NOP – Number of Parts JWL Panel Line 656; NOUP – Number of Unique Parts JWL Subassembly – 240; JWL – Joint Weld Length JWL Manual – 288

Disadvantages

- subassembly alignment is more difficult taking more time and man-hours to assemble by sliding floors qver longitudinals, and '
- high accuracy is required.

On the other hand, Case II longitudinal notch shape design uses chocks and thus has more parts, more joint weld length where hard to access, and more cutting length, but the alignment is easier than the other design.

In this example model, the production process consists of five workstations:

1. fabrication - cutting,
2. fabrication - bending,
3. subassembly,

TABLE 4.1V Man-hour Differences Between Case I and **II,** with Respect to Workstations

	Case I	*Case II*	*Difference]*	*Percent*[2]
Fabrication - cutting	56.2	57.7	1.4	2.4
Fabrication - bending	2.0	2.0	0.0	0.0
Sub-assembly	222.9	222.9	0.0	0.0
Assembly	397.9	578.0	180.0	31.2
Block construction	199.4	279.4	80.0	28.6
Total	878.5	1139.9	261.4	22.9

TABLE 14.V Man-hour Differences Between Case I and **II,** with Respectto Processes

	Case I	*Case II*	*Difference*	*Percent*
Manufacturing	326.3	687.8	361.4	52.6
Cutting	33.0	34.4	1.4	4.1
Forming	2.0	2.0	0.0	0.0
Edge milling & Misc	43.1	43.1	0.0	0.0
Welding	248.3	608.3	360.0	59.2
Material handling	552.2	452.2	-100.0	-22.1
Lift/turn-over	150.0	50.0	-100.0	-200.0
Aligning	382.2	382.2	0.0	0.0
Moverransport	20.0	20.0	0.0	0.0
Total	878.5	1139.9	261.4	22.9

4. assembly, and
5. block construction workstations.

And the shipyard model has NC plasma marking/cutting machine, semi-automatic edge beveling machine, profile NC marking/cutting machine, plate edge milling machine and rolling machine transfer conveyor in fabrication, two gantry cranes in subassembly, two gantry cranes, a hydraulic jack, automatic stiffener feeder in assembly, and two overhead bridge cranes and a transporter in block construction.

Table 14.IV shows the differences in man-hours between Case I and II, with respect to workstations. The total man-hours required to produce a double bottom block using Case I design is about 23 % less than that of Case II. The difference in man-hours ranges from 0 % in bending and sub-assembly to a high of 31 % in assembly workstation. The Case II using collar plates requires by far more man-hours in assembly and block construction, which could be reasonable due to the welding of collar plates in assembly and block construction workstation.

Although the longitudinal notch has more cutting length, Case I requires less man-hours in cutting. This is because Case II requires collar plate cutting as well as longitudinal notch cutting.

Table 14.V shows the man-hour differences between Case I and II, with respect to process. As can be seen, Case I requires more material handling man-hours, especially aligning, while Case II requires more manufacturing man-hours, especially welding. Although case II requires 22 % less man-hours in material handling processes, total man-hours are 23 % more than that of case I, due to the by far more man-hours in welding process for Case II.

The total man-hours, required to produce the double bottom block with Case I notch shapes, is about 23 percent less than that of Case II notch shape. The difference in man-hours ranges from zero percent in bending and subassembly to a high of 31 percent in block construction workstation. Case II requires more man-hours in assembly and block construction, which is due to the welding of collar plates in assembly and block construction workstations. Case I requires more material handling man-hours, especially aligning.

As in the example in subsection 14.3.4.2 the savings will be multiplied in way of transverse bulkheads.

1.1.3.6 Designing outthe need for high accuracy

Many structural details, especially those used in naval ship design, have connections that use butt weld connections. This type of connection requires high accuracy and significant man-hours for fitup. This can be avoided by using overlapping connections, such as the butted longitudinal connections by lapped connections as shown in Figure 14.55 and Figure 14.56 and the frame/beam brackets shown in Figure 14.62. Also the replacement of butt weld connections by fillet weld connections, as shown in Figures 14.54

14.4 BUILD STRATEGY APPROACH

All shipbuilders plan how they will design and build their ships. The plan may be only in someone's head or a detailed and documented process involving many people. Often different departments prepare independent plans, which are then integrated by a *Master Plan/Schedule.*

The *Build Strategy Approach* is much more than the normal planning and scheduling and a description of how the Production Department will build the ship.

Many shipbuilders use the term *Build Strategy* for what is only their Production Plan. This is incorrect. The term Build Strategy as originally developed in Britain and subsequently in the U.S. has a special, specific meaning. It is also recognized that some shipbuilders have a process very similar to the Build Strategy approach but do not call it such. The recent U.S. Navy/industry promoted *Design and Build Plan* has a lot of similarity to a *Build Strategy,* although it still allows the shipbuilders to ignore the important *Shipbuilding Policy* part of the Build Strategy Approach.

14.4.1 What is the Build Strategy Approach?

It was A&P Appledore that conceived and developed the formal Build Strategy Approach in the early 1970s. It developed from the ideas and processes generated to support the A&P Appledore associated *Ship Factories* at Appledore and Sunderland, in the U.K. The detailed work breakdown, formalized work sequencing and very short build cycles associated with these ship factories required the communication, coordination and cooperation that are inherent in the Build Strategy Approach.

British Shipbuilders adopted the Build Strategy Approach for all their shipyards (49,50) and A&P Appledore consulting group continued to develop the approach as a service to their clients.

The Build Strategy Approach was introduced into the U.S. by A&P Appledore's participation in IREAPS conferences, as well as through presentations to individual shipbuilders and the SP-4 Panel (14).

A&P Appledore consulting to NORSHIPCO, Lockheed Shipbuilding Company and Tacoma Boat introduced the use of the Build Strategy Approach to U.S. shipbuilding projects. The author was involved in a project to implement the Build Strategy Approach into U.S. shipbuilding (15). Finally, the Build Strategy Approach was described in the DESIGN FOR PRODUCTION Manual, prepared by A&P

Appledore for the SP-4 Panel (8) and in the revision of the DESIGN FOR PRODUCTION MANUAL (9).

It is a known fact, but, unfortunately, not an often practiced approach, that the performance of any endeavor will be improved by improvements in communications, cooperation and collaboration. The Build Strategy Approach improves all three. It communicates a shipyard's way of doing business, its preferred shipbuilding approach and practices, and the specifics for the intended shipbuilding project, to all participants. This communication fosters improved cooperation as everyone is working to the same plan. It improves collaboration by involving most of the stakeholders (interested parties) in its development.

The Build Strategy approach can be described by positioning the three parts at the comers of a triangle as shown in Figure 14.90. This shows the shipyard's Business Plan at the top being supported by the *Shipbuilding Policy* and the *Build Strategies.*

The business plan sets the company's vision for the immediate future. The shipbuilding policy develops the business plan into the preferred way the shipyard wants to achieve the business plan.

It covers use of facilities, how the different types of ships in its selected product range will be built, including their block breakdown and zone definition, and the processes to be used for design, purchasing, production and testing. In addition, the SP identifies productivity targets and future improvement plans. The SP also includes the shipyard's *Product-oriented Work Breakdown Structure* or *Interim Product Database.*

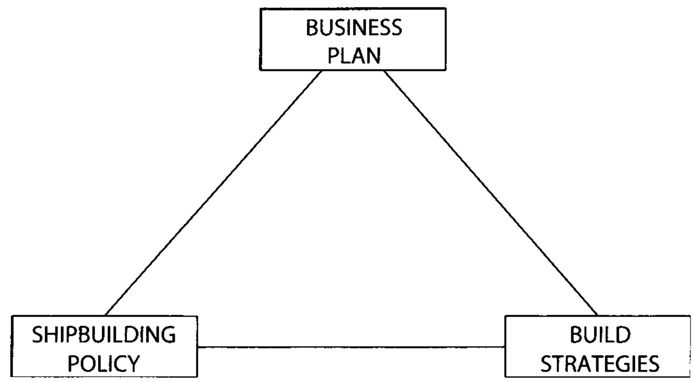


Figure 14.90 Build Strategy Approach Triangle

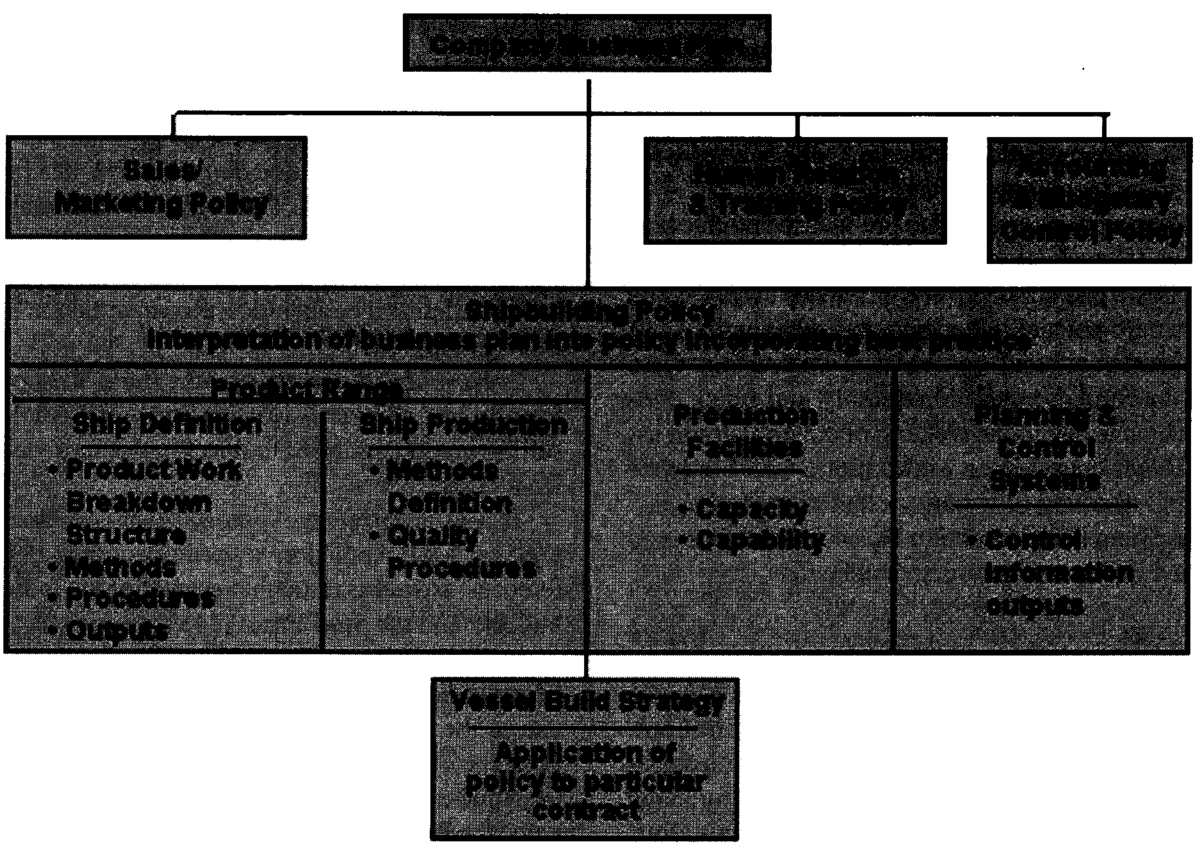


Figure 14.91 Build Strategy and Shipbuilding Policy

14.4.2 Shipbuilding Policy

A *Shipbuilding Policy* is the definition of the optimum organization and its operations, including the design and build methods required to produce the product mix contained within the company's shipbuilding ambitions, as defined in the Business Plan. The Shipbuilding Policy is aimed primarily at design rationalization and standardization, together with the related work organization, to simulate the effect of series construction.

This is achieved by the application of group technology and a product work breakdown, which leads to the formation of interim product families.

A Shipbuilding Policy is developed from a company's Business Plan, which usually covers a period of five years and includes such topics as:

- product range which the shipyard aims to build,
- shipyard capacity and targeted output,
- targets for costs, and
- pricing policy.

The product range is identified, usually as a result of a market study.

The relationship between a Business Plan, Shipbuilding Policy, and Build Strategy is shown in Figure 14.91.

The Business Plan sets a series of targets for the technical and production part of the organization. To meet these targets, a set of decisions is required on:

- facilities development,
- productivity targets,
- make, buy or subcontract, and
- technical and production organization.

These form the core of the Shipbuilding Policy. The next level in the hierarchy defines the set of strategies by which this policy is realized, namely the Build Strategy.

In essence, the Shipbuilding Policy comprises a set of standards which can be applied to specific ship contracts. The standards apply at different levels:

- *Strategic*, related to type plans, planning units, interim product types, overall facility dimensions, and so on; applied at the Conceptual and Preliminary Design stages,
- *Tactical*, related to analysis of planning units, process analysis, standard products and practices, and so on; applied at the Contract and Transition Design stages, and
- *Detail*, related to work station operations and accuracy tolerances; applied at the Detail Design stage.

Because shipbuilding is dynamic, there needs to be a constant program of product and process development. Also, the standards to be applied will change over time with product type, facilities, and technology development. The shipbuilding policy is therefore consistent, but at the same time will undergo a structured process of change, in response to product development, new markets, facilities development, and other variations. The policy has a hierarchy of levels, which allows it to be applied in full at any time to a particular contract.

Therefore, to link the current policy with a future policy, a series of projects for change should be incorporated into an overall action plan to improve productivity. Since facilities are a major element in the policy, a long-term development plan should exist which looks to a future policy in that area. This will be developed against the background of future business objectives, expressed as a plan covering a number of years.

These concepts are summarized and illustrated in Tables 14.VI and VII.

Work at the *Strategic* level provides inputs to:

- conceptual and preliminary design stages,
- contract build strategy,
- facilities development,
- organizational changes, and
- tactical level of shipbuilding policy.

TABLE 14.VI Elements of Shipbuilding Policy

POLICY OVERVIEW

Policy Based on Business Plan Objectives

Sets Objectives for Lower Levels

CURRENT PRACTICE

Existing Standards

Last Best Practice

Procedures to be Applied to Next Contract

PRODUCTIVITY ACTION PLAN

Covers Next Twelve Months

Plans Improvements in Specific Areas

Is a Set of Projects

FUTURE PRACTICE

Developed from Current Practice

Incorporates Outcome of Action Plan

Procedures to be Applied to Future Contracts

LONG TERM DEVELOPMENT PLAN

Covers Facilities Development

Covers a Five-Year Period

TABLE 14.VII Typical List of Contents in A Detailed Shipbuilding Policy Document

1.00VERVIEWN
1.1 Objectives
1.2 Purpose and Scope
1.3 Structure

2.0 PRODUCT RANGE
2.1 Product Definition
2.2 Outline Build Methods

3.0 OVERALL PHILOSOPHY
3.1 Outline
3.2 Planned Changes and Developments
3.3 Related Documents
3.4 Work Breakdown Structure
3.5 Coding
3.6 Technical Information
3.7 Workstations
3.8 Standards
3.9 Accuracy Control

4.0 PHYSICAL RESOURCES
4.1 Outline
4.2 Planned Changes and Developments
4.3 Related Documents
4.4 Major Equipment
4.5 Steel Preparation and Subassembly
4.6 Outfit Manufacture
4.7 Steel Assembly
4.8 Outfit Assembly
4.9 Pre-outfit Workstations
4.10 Berth/Dock Area
4.11 Engineering Department Resources

5.0 SHIP PRODUCTION METHODS
5.1 Outline
5.2 Planned Changes and Developments
5.3 Related Documents
5.4 Standard Interim Products, Build Methods
5.5 Critical Dimensions and Tolerances
5.6 Steel Preparation
5.7 Steel Assembly
5.8 Hull Construction
5.9 Outfit Manufacture
5.10 Outfit Assembly
5.11 Outfit Installation
5.12 Painting
5.13 Services
5.14 Productivity Targets
5.15 Subcontract Work

6.0 SHIP DEFINITION METHODS
6.1 Outline
6.2 Planned Changes and Developments
6.3 Related Documents
6.4 Ship Definition Strategy
6.5 Pre-Tender Design
6.6 Post-Tender Design

7.0 PLANNING FRAMEWORK
7.1 Outline
7.2 Planned Changes and Developments
7.3 Related Documents
7.4 Strategic Planning
7.5 Tactical Planning
7.6 Detail Planning
7.7 Performance Monitoring and Control

8.0 HUMAN RESOURCES
8.1 Outline
8.2 Planned Changes and Developments
8.3 Related Documents
8.4 Organization
8.5 Training
8.6 Safety

9.0 ACTION PLAN
9.1 Outline
9.2 Projects and Time Scales

At the strategic level, a set of documents would be prepared which address the preferred product range.

For each vessel type, the documents will include:

- definition of the main planning units,
- development of type plans, showing the sequence of erection, and
- analysis of main interim product types.

The *Strategic* level will also address the question of facility capability and capacity. Documentation on the above will provide input to the conceptual design stage except, of course, in those cases where a design agent is undertaking the design work and the builder has not been identified.

Documentation providing input to the preliminary design stage will include:

- preferred raw material dimensions,
- maximum steel assembly dimensions,
- maximum steel assembly weights,
- material forming capability, in terms of preferred hull configurations,
- *standard* preferred outfit assembly sizes, configuration and weights, based on facility capacity/capability, and
- *standard* preferred service routes.

At the *Tactical* level standard interim products and production practices related to the contract and transition design stages, and to the tactical planning level, will be developed. All the planning units will be analyzed and broken down into a hierarchy of products.

The policy documents will define preferences with respect to:

- standard interim products,
- standard product process and methods,
- standard production stages,
- installation practices,
- standard material sizes, and
- standard piece parts.

The capacity and capability of the major shipyard facilities will also be documented.

For the planning units, subnetworks will be developed which define standard times for all operations from installation back to preparation of production information. These provide input to the planning function.

At the *Detail* level, the policy provides standards for production operations and for detail design. The documentation will include:

- workstation descriptions,
- workstation capacity,
- workstation capability,
- design standards,
- accuracy control tolerances,
- welding standards, and
- testing requirements.

Reference to the standards should be made in contracts, and relevant information made available to the design, planning and production functions. As with all levels of the shipbuilding policy, the standards are updated over time, in line with product development and technological change.

A *Ship Definition* is a detailed description of the procedures to be adopted, and the information and format of that information to be produced by each department developing technical information within a shipyard. The description must ensure that the information produced by each department is in a form suitable for the users of that information. These users include:

- shipowners or their agents,
- shipyard management,
- classification societies,
- government bodies,
- other technical departments:
  - design and drawing offices,
  - CAD/CAM center,
  - lofting,
  - planning,
  - production engineering,
  - production control,
  - material control,
  - estimating,
  - procurement, and
- production departments

Preferably the ship under consideration would also be of a type that has been identified in the Shipbuilding Policy as one which the shipyard is most suited to build.

While the scope of the Shipbuilding Policy requires that it be developed by a cross-functional team with members from all departments in a shipyard, it is clear that it would benefit from utilizing Concurrent Engineering (CE) in its development. However, its existence negates the need for CE in subsequent activities as all the decisions have been made and documented in the Shipbuilding Policy.

The very act of developing a Shipbuilding Policy will have benefits due to the fact that it requires the various departments involved to communicate and to think rationally about how and where the work for a particular contract will be performed. It will also highlight any potential problems and enable them to be addressed well before the *traditional* time when they will arise.

A Shipbuilding Policy is a *seamless* document. It crosses all traditional department boundaries. It is an important step in the direction of the *seamless enterprise.* The most evident benefit is improved communication brought about by engaging the whole company in discussions about project goals and the best way to achieve them. It eliminates process/rework problems due to downstream sequential hand-over of tasks from one department to another by defining concurrently how the ship will be designed and constructed.

Some of the advantages mentioned by users of the Build Strategy Approach are:

- serves as an effective team building tool,
- requires that people share their viewpoints because they need to reach a consensus,
- places engineers face to face with their customers, namely purchasing, production, test, etc.,
- expands people's view of the product (ship) to include such aspects as maintenance, customer training, and support service,
- fosters strong lateral communication,
- saves time through concentration on parallel versus sequential effort,
- facilitates resolution of differences and misunderstandings much earlier,
- greatly improves commitment *(buy in)* by participants and the effectiveness of the hand-over later,

- serves as a road map that everyone can see and reference as to what is happening,
- facilitates coordinated communication, and
- develops a strong commitment to the process and successful completion of the project.

There are a few disadvantages mentioned by some users, such as:

- effort and time to prepare the formal Build Strategy document,
- total build cycle appears longer to some participants due to their earlier than normal involvement,
- cross-functional management is not the norm and most people currently lack the skills to make it work,
- experts who used to make independent decisions may have difficulty sharing these decisions with others in developing the Build Strategy, and
- a Build Strategy describes the complete technology utilized by a shipyard and if given to a competitor, it could negate any competitive advantage.

However, the users felt that the advantages greatly outweigh the disadvantages.

14.4.3 Why Should Shipbuilders Use the Build Strategy Approach?

If mass production industries, such as automobile manufacture, are examined, there is no evidence of the use of build strategies.

Some shipyards that have a very limited product variety, in terms of interim and final products, generally speaking, also have no need for build strategies, due to their familiarity with the products. If such shipyards, which are among the most productive in the world, do not use build strategies, then why should a shipbuilder adopt the Build Strategy Approach?

The answer lies in the differences in the commercial environments prevalent and the gearing of operating systems and technologies to the product mix and marketing strategies. In a general sense, the most productive yards have identified market niches, and have developed suitable standard ship designs, standard interim products, and standard build methods. By various means, these yards have been able to secure sufficient orders to sustain a skill base, familiar with those standards. As the degree of similarity in both interim and final products is high, there has been no need to re-examine each vessel to produce detailed build strategies, but many of them do, as they find the benefits greatly outweigh the effort. Also, the Build Strategy Approach will ensure that the way they are to be applied is well planned and communicated to all involved.

Most shipyards have elements of a Build Strategy Document in place. However, without a formalized Build Strategy Document the lines of communication may ~ too informal and variable for the most effective strategy to be developed.

A well-organized shipyard will have designed its facilities around a specific product range and standard production methods, which are supported by a variety oftechnical and administrative functions that have been developed according to the requirements of production, and detailed in a Shipbuilding Policy. In this case, when new orders are received, only work that is significantly different from any previously undertaken needs to be investigated in depth in order to identify possible difficulties.

Where it has not been possible to minimize product variety, such investigations will become crucial to the effective operation of the shipyard. The outcome of these investigations is the Shipbuilding Policy document.

14.4.4 Build Strategy

A Build Strategy is a unique planning tool. By integrating a variety of elements together, it provides a holistic beginning to end perspective for the project development schedule. It is also an effective way of capturing the combined design and shipbuilding knowledge and processes, so they can be continuously improved, updated, and used as training tools.

A Build Strategy effectively concentrates traditional meetings that bring all groups involved, together to evaluate and decide on how the ship will be designed, procured, constructed, and tested before any tasks are commenced or any information is *passed on.*

The objectives of the Build Strategy Document are to identify:

- the new vessel,
- the design and features of the new vessel,
- contractual and management targets,
- departures from the shipyard's Shipbuilding Policy.
- constraints, based on the new vessel being designed/constructed, particularly with reference to other work underway or envisaged.
- what must be done to overcome the above constraints.

The last objective is particularly important, as decisions taken in one department will have implications for many others. This means that effective interdepartmental communication is vital.

If a Shipbuilding Policy exists for the company, then it should be examined in order to ascertain if a ship of the type under consideration is included in the preferred product mix. If such a ship type exists then certain items will already have been addressed. These items include:

- outline build methods,
- work breakdown structure,
- coding,
- workstations,
- standard interim products,
- accuracy control,
- ship definition methods,
- planning framework,
- physical resources at shipyard, and
- human resources.

The Build Strategy applies the shipbuilding policy to a specific ship contract. A Build Strategy:

- applies a company's overall shipbuilding policy to a contract,
- provides a process for ensuring that design development takes full account of production requirements,
- systematically introduces production engineering principles that reduce ship work content and cycle time,
- identifies interim products and creates a product-oriented approach to engineering and planning of the ship,
- determines resource and skill requirements and overall facility loading,
- identifies shortfalls in capacity in terms of facilities, manpower and skills,
- creates parameters for programming and detail planning of engineering, procurement and production activities,
- provides the basis on which any eventual production of the product may be organized including procurement dates for *long lead* material items,
- ensures all departments contribute to the strategy,
- identifies and resolves problems before work on the contract begins, and
- ensures communication, cooperation, ~ollaboration and consistency between the various technical and production functions.

In summary, *a Build Strategy* is *an agreed design, material management, production and testing plan, prepared before any work starts, with the aim of identifying and integrating all necessary processes.*

The Build Strategy is used to facilitate and strengthen the communication links. It should be up front and be used to resolve potential conflicts between departments in areas of design details, manufacturing processes, makelbuy decisions, and delivery goals. The intent of a Build Strategy is to disseminate the information it contains to all who can benefit from knowing it. Throughout this chapter it is described as a hard copy document, but today it could well be electronically stored and disseminated through local area network workstations.

A Build Strategy can also be used as an effective people empowerment tool by giving participants the opportunity to work out all their needs together in advance of performing the tasks.

The Build Strategy Document should be used by all of the departments involved in designing, planning, procuring material, material handling and building the ship, and a formal method of feedback of problems and/or proposed changes must be in place so that agreed procedures cannot be changed without the knowledge of the responsible Build Strategy team/committee. Any such changes must then be passed on to all holders of controlled copies of the Build Strategy.

Producing a Build Strategy Document will not guarantee an improvement in productivity, although, as stated earlier, the process of producing the document will have many benefits. Full benefits will only be gained if the strategy is implemented and adhered to. Positive effects of the Build Strategy approach are two fold:

- Prior to production, the use of the Build Strategy Approach ensures that the best possible overall design and production philosophy is adopted. Crucial communication between relevant departments is instigated early enough to have a significant influence on final costs. It is therefore the structured, cross-discipline philosophy, which provides the downstream reductions in costs, and this is the major benefit.
- During production, managers and foremen have a guidance document, which ensures that they are fully aware of the construction plan and targets, even those relating to other departments. This reduces the likelihood of individual making decisions which have adverse effects in other departments.

A shipyard, which develops a strategy by this method, will gain all the advantages, whether or not a single Build Strategy Document is produced. However, the imposition of the requirement for a single document should ensure that the development of the strategy follows a structured approach.

14.4.4.1 Prerequisites for a build dtrategy

A Build Strategy could be produced as a stand-alone document for any ship to be built by a shipyard, without having a Shipbuilding Policy for the shipyard, as is done in many U.S. shipyards, but it is a waste of effort by having to repeat the information that should be in the Shipbuilding Policy. It also runs the risk of having different design and building methods for different Build Strategies.

It is argued that, for shipyards that cannot define a narrow range of ship types, because of a low demand for the ships, and therefore have to be flexible and willing to build any type that comes along, preparing a Shipbuilding Policy would not be effective. This is not the case, as it is easier and faster to modify the shipbuilding approach and practices in an existing Shipbuilding Policy and this would still ensure that the same team that produced the Shipbuilding Policy would be responsible for the modificatiOns for the new ship type.

It is believed that shipyard management is reluctant to

TABLE 14.111 Proposed Build Strategy Document Contents

1: INTRODUCTION		
1.1	Purpose of Document	R[1]
1.2	Build Strategy Document Prerequisites	R
1.3	Distribution	R
1.4	Summary	R
2: VESSEL DESCRIPTION		
2.1	General Description & Mission	R
2.2	Principal Particulars	R
2.3	Special Characteristics & Requirements	R
2.4	Comparisons/Differences From Previous Vessels	R
2.5	Applicable Regulations & Classification	O
2.6	Owner Particulars	
2.6.1	Background	O
2.6.2	Fleet	O
2.6.3	Past Relationship	O
2.6.4	Competition	O
3: CONTRACTUAL		
3.1	Contractual Dates & Time Constraints	R
3.2	Payment	O
3.3	Liquidated Damages & Penalties	R
3.4	Cancellation	O
3.5	Drawing Approval	O
3.6	Construction Inspection	O
3.7	Trials	O
3.8	Quality	R
4: DESIGN & ENGINEERING		
4.1	Strategy & Scope	
4.1.1	General	R
4.1.2	Changes to Ship Definition Strategy	R
4.1.3	Modeling & Composites	R
4.2	Key Drawings	R
4.3	Production Information Requirements	
4.3.1	CAM Information	R
4.3.2	Manufacturing Information	R
4.3.3	Parts Listings	R
4.3.4	Installation Drawings	R
4.3.5	Installation Procedures	R
4.4	Design & Engineering Schedule	
4.4.1	Schedule	R
4.4.2	Resourcing & Utilization	O
4.4.3	VFI Schedule	R
4.5	Datum's & Molded Definition	O
4.6	Design Standards	R
4.7	Functional Space Allocations	R
4.8	Detail Design Guidelines	
4.8.1	Steelwork	O
4.8.2	Machinery	O
4.8.3	Pipework	O
4.8.4	Electrical	O
4.8.5	Joinerwork	O
4.8.6	Paintwork	O
5: PROCUREMENT		
5.1	Master Material List	O
5.2	Master Equipment List	O
5.3	Material Procurement Strategy	O
5.4	Procurement Schedule	R
5.5	Critical/Long Lead Items	R
6: PLANNING & PRODUCTION		
6.1	Strategic Planning	
6.1.1	Key Event Program	R
6.1.2	Resourcing & Utilization	O
6.1.3	Changes to Shipbuilding Policy	R
6.1.4	Required Facility, Tooling & Equipment Upgrade	R
6.2	Work Breakdown	
6.2.1	Work Breakdown Structure	R
6.2.2	Coding	R
6.3	List of Planning Unit	
6.3.1	Hull Blocks	R
6.3.2	Zones	R
6.3.3	Equipment Units	R
6.3.4	Systems	R
6.4	Master Schedules	
6.4.1	Hull Blocks	R
6.4.2	Zones	R
6.4.3	Equipment Units	R
6.4.4	Systems	R
6.5	Hull Production Strategy	
6.5.1	Preliminary Process Analysis	O
	-Integration of Outfit	
	-Process Analysis by Block	
6.5.2	Non-standard Interim Products	O
6.5.3	Build Location & Launch Condition	R
6.5.4	Erection Schedule	R
6.6	Machinery Space Outfit Strategy	
6.6.1	Equipment Units	R
6.6.2	On-block Outfitting	R
'6.6.3	On-board Outfitting	R
6.7	Accommodation Outfit Strategy	R
6.8	Cargo & Other Space Outfit Strategy	
6.8.1	On-block Outfitting	R
6.8.2	On-board Outfitting	R
6.9	Painting Strategy	
6.9.1	Outline Paint Specification	O
6.9.2	Pre-Painting	R
6.9.3	Primer Repair Strategy	R
6.9.4	Unit/Block Painting Strategy	R
6.9.5	Zone Painting Strategy	R
6.9.5.1	Machinery Spaces	
6.9.5.2	Outside Shell and Decks	
6.9.6	Special Considerations	R
6.10	Sub-Contract Requirements	
6.10.1	Bought-In Items	R
6.10.2	Use of On-Site Sub-Contractors	R
6.11	Productivity	
6.11.1	Productivity Targets	R
6.11.2	Comparisons/Differences From Previous Vessels	R
6.12	Temporary Services	
6.12.1	Staging Plan	R
6.12.2	Access & Escape Plan	O
6.12.3	Power & Lighting	O
6.12.4	Weather Protection	O
7: ACCURACY CONTROL MANAGEMENT PLAN		
7.1	System Critical Dimensions & Tolerances	R
7.2	Interim Product Critical Dimensions & Tolerances	R
7.3	Sampling Plan	O
7.4	Special Procedures	O
7.5	Jigs & Fixtures	O
7.6	Hot Work Shrinkage	
7.6.1	Use of Extra Stock	O
7.6.2	Shrinkage Allowances	O
7.6.3	Distortion Control	O
8: TEST & TRIALS		
8.1	Test Planning	
8.1.1	Strategy	R
8.1.2	Schedule (High Level)	R
8.2	Pre-Completion Testing	
8.2.1	Pre-Survey & Dry Survey	O
8.2.2	Pipe Pre-Testing	O
8.2.3	Equipment Unit Pre-Testing	O
8.3	Tank Test Schedule	R
8.4	Equipment Unit Test Schedule	R
8.5	Pipe Unit Test Schedule	R
8.6	Zone Close-Out Strategy	R
8.7	Principal Trials Items	R
9: PERSONNEL		
9.1	Industrial Relations Aspects	
9.1.1	Design	O
9.1.2	Sub-Contract	O
9.2	Training	O
9.3	Project Organization	
9.3.1	Shipyard Organization Charts	R
9.3.2	Client's Organization Charts	R
10: WEIGHT CONTROL		
10.1	General	
10.2	Outline Procedure	R
10.3	Departmental Responsibilities	

1. R is recommended, O is optional.

spend its own money on actions that would benefit all projects, and would rather spend the customer's money on each project. This attitude is only sustainable in a captive or protected market and is not acceptable in a truly competitive market where every opportunity to save effort and improve a company's competitive position is the goal.

14.4.4.2 Build Strategy document contents list

A contents list, shown in Table l4.VIII, was developed for the NSRP Build Strategy project (15). The actual Build Strategy Document and the two examples followed this contents list. An introduction outlining the purpose of the Build Strategy Document, its suggested distribution in a shipyard, and the prerequisites for a successful Build Strategy was also provided.

14.5 REFERENCES

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Chapter 15

Human Factors in Ship Design

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15.1 Introduction

Human Factors, Human Centered Design, Ergonomics ... these are examples of terms that have been used interchangeably to describe the practice of designing a system with the human operator as the central focus. Although these terms and the principles they embrace are not new, they are critical aspects of engineering design. Traditional marine design and operation has not employed these concepts to the full extent possible. Therefore, this chapter was written to broaden the ship designer's understanding of human factors and to introduce design elements and principles that have significant effects on the shipboard human operator. This is important to an engineer because addressing human factors in ship design significantly reduces production and operation costs and improves overall safety.

Decades of engineering practice have undoubtedly proven that the human operator is a complex variable that warrants significant consideration during the first stages of design and throughout the entire operational lifetime of a system. However, human factors are frequently neglected during the design process and during the systems operation. When human factors are not adequately addressed, people make errors and safety is severely compromised, the consequences of which are well documented.

Chemobyl, Bhopal, and Three Mile Island, which resulted in tens of thousands of deaths and injuries, are examples of major industrial mishaps that resulted from insufficiently addressing human factors in a system's design and operation. Maritime examples include the loss of the North Sea platform *Piper Alpha* (Figure 15.1) and the drilling rig *Ocean Ranger*. These maritime incidents resulted in 250 deaths and the loss of hundreds of millions of dollars of physical assets. All of these events were the result of a long chain of human errors that resulted in human factors oversights. These well-publicized events represent but a few of the many mishaps that can be attributed to human error.

The true significance of human error caused by ignoring human factors is reflected in the following statistics. These values signify the considerable degree to which human error was either the root cause or a major contributing factor:

- 65% of all airline accidents,
- 80% percent of all maritime casualties,
- 90% of all auto accidents, and
- 90% of all nuclear facility emergencies.

The long list of mishaps that make up these statistics have a common factor, they involved systems and equipment that failed because the human operator was a secondary consideration in the design process. This design practice results in equipment or systems that are not well designed to meet a human being's physical or cognitive capabilities, and therefore, forces individuals to adapt to the system. This practice is exactly what human factors attempts to prevent. Designing a system or creating an organization that incorporates human factors into the design criteria from the earliest stages creates an optimal environment for maximum human performance and has a direct impact on preventing mishaps.

Preventing mishaps is not the only positive effect of ad-

Figure 15.1 *Piper Alpha* Disaster

dressing human factors in systems design. Human factors also provides significant increases in job performance and improves decision making, in addition to reducing costs by decreasing training and maintenance requirements. Cost has always been a major design constraint for most systems and incorporating human factors into a system's design may significantly reduce it. Many people view human factors and hiring Human Factors Engineers as an added cost. However, it has been proven that addressing human factors in systems design actually reduces costs. This is the result of many factors, including reduced manning, reduced need for training, and improved maintainability.

This chapter discusses areas such as environment, equipment, and training to explain how human error can be significantly reduced if human factors are adequately considered in the design and operation of a system. The purpose of this chapter is to describe and discuss human factor requirements, challenges, design approaches, and tools to be used in the design of marine systems. More importantly, the chapter emphasizes the need to incorporate human factors into the design process from the very beginning.

15.2 Human Factors

Before continuing with a discussion of human factors, it may be useful to present a more formal definition of the concept and some of its history. *Human Factors, Human Factors Engineering, Human Engineering* and *Ergonomics* have all appeared interchangeably throughout engineering literature. For the purpose of our discussion, Human Factors is the comprehensive term that covers all biomedical and psychosocial considerations applying to the human in the system. Human factors, addresses human engineering and\also life support, personnel selection, training and training equipment,job performance aids, and performance measures and evaluations (1). Human factors is concerned with every consideration of the human in the system, that is, reasons for being in the system, functions and tasks, the design of jobs for various personnel, training and evaluation.

The importance of human factors can be observed by the recent efforts within both government and industry to support and embrace the concepts of human factors and systems engineering. For example, human factors have been incorporated into programs such as Human Systems Integration (HSI) within the U.S. Navy, MANPRINT in the U.S. Army, Crew Systems Integration in NASA, and Prevention through People (PTP) within the U.S. Coast Guard.

The term Human Factors Engineering (HFE) is only one of the many aspects of design that are addressed within human factors. HFE mainly attends to the issues of layout, equipment design, and workplace environment. HFE also address human-machine interface, including displays and controls. Human Factors Engineering in ship design includes:

- techniques to define the role of the human in complex systems,
- simulation and modeling of crew workloads for manning reduction and assessing operator/maintainer workloads,
- advanced man-machine interfaces and decision aids to reduce human error and accidents and enhance human performance and safety, and
- ship design methods and data.

15.2.1 Historical Perspective

There exists a select group of individuals and historical events that mark the rise and progression of human factors. According to Burgess (2), Human Factors Engineering and Ergonomics are relatively new terms that were first used in the 1940s, but human factors work had been done well before that. The following items are a small sampling of some of these events:

- in 1832, Charles Babbage laid out the methods for making workers' jobs easier and more economical in his book, *Economy of Machinery and Manufacture.*
- in the 19th century, Frederick Taylor, who is perhaps the first human factors engineer, developed a number of tools and methods to increase production. In 1898, he conducted studies to find the most appropriate designs for

shovels, and his experiments in lifting and carrying heavy loads improved overall production and reduced worker fatigue (2,3).

- during World War I, United States and United Kingdom governments directed significant attention to military personnel selection and training. Their prime target effort was *fitting the man to the job.* In 1918, the U.S. established laboratories at Wright-Patterson Air Force Base and the Brooks Air Force Base to perform human-factors-related research. Since then, these labs have performed research on areas such as complex reaction time, perception, and motor behavior (4).
- in the 1920s and 1930s, the Gilbreaths studied various methods that could allow physical tasks to be performed with less effort and greater speed. In 1911, Frank B. Gilbreath's analysis of bricklaying resulted in the invention of scaffolding which could be raised and lowered quickly, allowing bricklayers to work at the most suitable level at all times (2,5).
- in World War II, human factors applications became widespread when machines increased in their complexity and poor human engineering resulted in the loss of lives and equipment (2). According to Dhillon (5), the years between the two world wars saw major growth in industrial psychology and industrial engineering.
- within the military and the manned space programs of 1950s and 1960s, human factors truly emerged as a specialty, according to Huchingson (1).

This abbreviated collection of historical events within the human factors discipline clearly indicates that it is not a fledgling subject in design. Even so, it is an area that is frequently not given the attention that it deserves.

152.2 Human Factors: Objective, Characteristics, and Payoffs

When classifying a ship as a system, one observes that the central component essential to the success and operation of the system is the human being. Granted, in today's highly advanced world, computers and automated systems have replaced humans in many functions. However, the fact remains that humans ultimately are responsible for a ship's safe and effective operation. It is with this mentality that the designer needs to consider how the human will be able to perform within this system called a "ship."

According to Bost (6), there are several inherent qualities of humans that govern the way in which ship designers must account for in their designs. The following qualities are key ideas within human factors:

- people behave on the basis of homeostatic behavior (that is, the least amount of energy is expended to accomplish a given task in a perceived safe manner),
- equipment designs and procedures can induce even the most safety conscious person into committing unsafe acts,
- equipment designs and written procedures that do not match the operator /maintainer's cultural expectations will eventually result in a user error,
- if printed procedures or hazard identification signs are perceived to be too complex, lengthy, or frequent, people tend to avoid reading them. Conversely, if they are perceived to be too simple, people also tend to ignore them,
- humans make guesses as to what a label, operating instruction, maintenance step, etc., says if it is not complete and readable.
- ease of equipment maintenance positively affects its reliability,
- equipment susceptibility to operational misuse or poor maintenance increases as the amount of physical or communicative interaction between two or more people increases,
- people often make judgments about how a controVdisplay works based on the controVdisplay shape, size, and orientation, and
- the musculo-skeletal system controls the direction and amount of force that can be applied by a person in completing an operational or maintenance task.

With these qualities in mind, the next issue to address is the relative objectives and the subsequent payoffs of implementing a human factors approach to design. Huchingson (1) effectively summarizes the objectives of a successful human factors program as follows:

- improved human performance as shown by increased speed, accuracy, and safety, and less energy expenditure and fatigue,
- reduced training and training costs,
- improved use of manpower through minimizing the need for special skills and aptitude,
- reduced loss of time and equipment as accidents due to human errors are minimized, and
- improved comfort and acceptance by the user/operator.

Bost (6) also points out that human factors engineering addresses the design of *human-machine inteifaces,* which are defined as any direct contact with software, equipment, manuals, signs, etc., that use any of the human's sensory receptors or motor responses. The navigation bridge of a vessel is a useful illustration of this *human-machine interface* (Figure 15.2).

The end result of incorporating a design, which accounts for human abilities and limitations, is a system, piece of equipment, or facility, which is:

- easily usable,
- quickly learnable,
- more repairable and supportable,
- more survivable,
- safer and more secure, more effective, and
- more adaptable to user needs.

From a wider perspective, Human Factors Engineering results in more economical and affordable systems, equipment, and facilities with reductions in: system costs, acquisition costs through a reduction of the costs of software redesign, acquisition costs through more effective man-machine interface design, life cycle costs through reduction of system manning, and life cycle costs through reduction of training (6).

As an example, the Navy has been modifying their acquisitions criteria to include Total Ownership Cost (TOC). This is a significant departure from the traditional method of obtaining the required system performance for the lowest procurement cost. TOC incorporates *all* funding for life cycle costs and includes those costs related to training, personnel, maintenance, disposal, etc. This shift of focus toward TOC is more cost effective since it considers human tradeoffs from the very beginning, as well as throughout, the design process.

It must be kept in mind that human factors engineering, just as any engineering discipline, is an iterative process that requires continuous measurement and evaluation. Burgess puts it best:

> Human interactions occur throughout the life of the machine or equipment and the operational product must be repeatedly interfaced throughout its life.

Usually, the first indication of a human factors design problem is when a user determines that other people are making the same mistakes, suggesting that poor design is the issue rather than training. It is at this point that the designer looks for alternative methods for designing the equipment or conducting the procedure, and these new approaches are tested to determine which is the better design solution.

15.2.3 Human Factors: Systems Concepts

Addressing human factors in ship design requires some understanding of systems and systems design. There are many definitions of and approaches to describing a system, however, it is generally agreed to be *a set of components that work together to achieve a common goal(s).*

Figure 15.2 Cruise Ship *Ocean Majesty*

Examples of common systems include a ship's navigation or propulsion system and the human nervous system. The components within each of these systems are interdependent and not necessarily linearly related. Moving up a dimension, the systems that comprise the ship as a whole are not designed in a vacuum only to be pulled together at the end. Rather, they must be coordinated at all stages of the design process and human factors must be considered at each phase of the design.

Humans interact with systems in many ways. From the drawing board to the scrap yard, humans have a significant effect on a system's effectiveness and safety. Meister (7) refers to a system more specifically as an organization of machine components that interact both with each other and with the human operator. The components not only interact with each other physically, but also interact with the operator by providing signals. There is also a behavioral component to the system, as these signals are interpreted by the operator and acted upon. The human operator may be regarded as either an internal or external element in a systems design, both of which can be argued equally valid. For the purposes of this chapter, the human operator is considered an internal component of a system's development since this is most applicable to the naval architect.

With a better understanding of systems and system development, designers can more effectively address human factors issues in the design process. There are a variety of excellent sources addressing human factors in systems design and they are provided as references at the end of this chapter.

Prior to designing and operating an actual system, a model and framework for analyzing the system must be developed. This model helps the design team understand how to design the system so that it is compatible with the human operator. There are numerous variables to be addressed that depend on the complexity of the system. Meister (4) lists several examples of system variables as follows:

- system organization,
- personnel,
- inputs,
- outputs,
- performance criteria, and
- environmental factors.

Personnel are extremely important variables since optimizing the number of personnel within a system is often a primary goal. This is a complex issue for the designer since a balance must be attained between how the ship functions are allocated between the people and the machinery or automation. There are also many considerations regarding the amount of experience and training the operator may need.

Workload and human performance are also directly related. This relationship must be considered in the design of a system since insufficient workloads tend to decrease performance from lack of interest and boredom, while excessive workloads can fatigue the operator and quickly surpass any human's abilities. It is incumbent upon the designer to find an adequate balance between workload and performance.

Designing and operating a system with human factors in mind pays great dividends. The overall cost of the system can be significantly lowered and the humans within the system are more safe and productive. However, failure to address human factors usually results in a significant increase in *human error*, which can lead to catastrophic mishaps.

15.2.4 Human Factors: Human Error

The subject of *human error* is well documented and referenced within the literature. This chapter is not intended to make the reader an expert in human error analysis; however, it is beneficial to possess a brief understanding of human error and how it influences human factors in ship design.

Bea (8) defined human error, including *organizational error*, as

> a departure from acceptable or desirable practice on the part of an individual or group that can result in unacceptable or undesirable results. Human Error refers to a basic event involving a lack of action or an inappropriate action taken by individuals that leads to unanticipated and undesirable results.

There are many factors that increase the likelihood of human error. These factors can generally be classified into categories, such as the following:

- *Organizational* factors have a significant effect on human error. Management plays a major role in developing and .. administering policy, creating corporate safety culture, and ensuring operational procedures are in place and practiced. The organization is also responsible for ensuring that the design of their systems pays close attention to human factors.
- *Personnel* on an individual level also playa significant role in human error. Examples of factors influencing human error on the individual level are fatigue, inattention, carelessness, inexperience, poor training, stress, etc. Although these factors result from human error at the individual level, many of these factors are within the control of the Organization, as described above.
- *Environmental* factors including poor equipment design, inadequate maintenance, poor workplace layout, weather, personnel interactions, etc., may contribute to human error.
- *Knowledge* at the organizational and individual level affects human error. For example, the general technical knowledge that exists, along with knowledge of the system's operation and proper operational procedures, all playa role in human error (9).

By addressing the above factors during the early design stages, relevant problem areas and concerns may be changed quite easily. Neglecting to account for these criteria leads to later realization that a system is not *human-friendly* or requires significant amounts of training, thus adding considerably to the cost.

15.2.5 Human Factors: Human Performance

Optimizing human performance relates directly to issues of knowledge superiority, effective decision-making, and better end-results regardless of the type of system. Human performance is affected by such factors as situational awareness and workload and it's essential to ensure that those tasks assigned to people are those that they can do well. For those tasks that are not conducive to humans' performance, they should be automated. For example, requiring a person to only monitor screens is a poor choice. This is a non-stimulating mental task that is usually somewhat boring, allowing the operator's attention to wander. It's important to note that when the decision is made to automate certain functions, it must be done so that the operator is fully aware of the system's status and has the ability to intervene when necessary.

Human performance must be measured by considering workload, attention, situational awareness, and the timeliness and accuracy of actions. The designer must ensure that none of the operator modalities, including cognitive, audio, visual, or psychomotor, discussed in Section 15.3, are overloaded. This can have a serious impact on situational awareness and therefore decision-making ability, creating an end result that may be far from optimal.

15.3 Human Capabilities and Limitations

Before embarking on the principles and guidelines that embody human factors engineering, it is necessary to briefly outline the central focus of this discipline: the human. Huchingson (1) notes that by studying and acquiring knowledge of basic human capabilities and limitations, the designer may create an environment that better suits human limitations, both functionally and physically.

Human beings come in a wide variety of shapes, sizes, and ages and thus a wide scope of abilities. The human operator has limitations on sensorimotor and information-processing capabilities, which must be considered in design. Each particular sensory organ responds to a specific energy system and is sensitive only to a certain range and magnitude of stimulation within the different classes of stimuli encountered in machine environments. Therefore, humans are inherently limited by cognitive and physical attributes in their response capabilities.

Cognitive capabilities are those that involve mental tasks and intellectual abilities, for example, reasoning, judgment, memory, audio/visual stimuli, and mental processing of events. *Physical attributes* include hand-eye coordination, strength and speed of muscular contraction, flexibility, and motor control. With this in mind, it is not the authors' intent to turn naval architects into human physiologist and behaviorists; however, an abbreviated understanding of some of these characteristics and limitations will better equip the designer with crucial information necessary to optimize human performance and minimize human error.

One factor that significantly affects human performance and increase human error is fatigue. Fatigue impairs performance in many ways and this will be discussed later in the chapter. Also, design considerations that reduce and prevent human fatigue will be discussed. This will provide the ship designer with an understanding of design elements that influence fatigue as well as the consequences of ignoring fatigue-inducing situations.

15.3.1 Cognitive Attributes

Tasks on board ships today, whether they include tracking a blip on radar, writing a sentence, listening to a direction, or adding a set of numbers to plot a course, require human cognitive and psychomotor abilities such as mathematical reasoning, verbal comprehension and reasoning, and visual perception. Humans' cognitive processes are responsible for receiving and analyzing this information received by the senses, and although there are five sensory transmission pathways, 90% of all sensory input is received through only two senses: sight (70%) and hearing (20%). According to Burgess (2), humans have limitations on their information processing capabilities, which stem from a variety of factors:

- expectancies,
- memory and data processing,
- emotionalism,
- boredom, and
- sensitivity to stress.

15.3.1.1 Expectancies

Human expectancies regarding the way things operate are a significant influence to the decisions people make. Huchingson (I) even states that population stereotypes are the single most important concept in the interpretation of displayed information, and that when design practices conflict with ingrained responses, the potential for human error dramatically increases. Cultural expectations, or population stereotypes, can be defined as the act of expecting certain things to always work in a fixed manner, or associating meaning to colors, shapes, etc., because one's culture has assigned such relationships.

Typical examples for North American culture include:

- reading text from left to right, and top to bottom,
- interpreting the color red to mean danger,
- expecting valve handles to open in a counter-clockwise direction, and close in a clockwise direction, and
- expecting T-bar handles as an invitation to pull, and mushroom head buttons as an invitation to push.

In addition to people's expectations, people often make judgments about how a control or display works based on its shape, size, and orientation (6). Therefore, it's crucial to account for the spatial relationships in design. In other words, place multiple but separate components of a system together so it is visually obvious that they are related and used together. Design and place panels, consoles, and work stations, and the individual controls and displays on these panels, so that the displays and controls are arranged, as viewed by the operator, in the same spatial relationship as is the actual equipment or system installed in the structure (6). During times of stress, it is especially important to consider cultural expectations because it is during these times when humans typically revert to what they have learned and come to expect.

15.3.1.2 Memory and data processing

A person's memory and data processing ability is limited by short-term memory and information encoding/transformation capabilities. In other words, extensive time, training, and rehearsal are necessary to interpret, translate, and process information in making complex decisions or performing multiple operations in a given time period. According to Huchingson (1), the *magic number seven* is suggested as a limit for processing information in one stimulus dimension. For example, it was found that listeners could sort pitch tones into about seven different *pigeonholes*, regardless of the number of different tones given or where they appeared on a frequency scale.

15.3.1.3 Emotionalism and boredom

Emotionalism and boredom also limit a human's information processing capability. For example, social tensions and conflicts are likely to impair or degrade performance, as are long duty cycles and repetitious tasks. Inadequate or poor quality sleep can also negatively affect a person's performance. More on this subject will be discussed in following sections.

15.3.1.4 Sensitivity to stress

Finally, an individual's sensitivity to stress is directly correlated to information processing capabilities. Moderate levels of stress are generally stimulating, or enhance performance. Response to these levels of stress varies with a person's background and individual skill level. Decision performance accuracy will generally decrease when the operator is required to respond more rapidly than he or she is capable of responding *(speed stress)* or when required to respond at the same rate but to a greater number of stimuli *(load stress) (1).*

In terms of a process, humans:

- receive information through their senses,
- process that information, and
- then respond to what is processed.

After action has been taken, humans use their senses again to collect data, process the accuracy of the actions taken, and then continue with a given action. This system may be referred to as a *closed loop system* may be interrupted between any of these actions. For example, sensory information may be delivered, but in such a way that it is imperceptible to the human (inaudible noise frequencies, ultravioletfmfrared light waves). Under these circumstances, the operator must make certain assumptions, which mayor may not be correct, in order to continue. It is at these breaks in the sensory loop that accidents and errors are most likely to occur.

15.3.2 Physical Attributes

Like any machine, the *human machine* has physicallimitations within which it must operate. These limits encompass structural characteristics such as the maximum force or velocity a muscle contraction can induce a limb to move, the physical dimensions of the human, and operating ranges within various environmental conditions such as light intensity and visible spectrum, temperature, and noise.

15.3.2.1 Anatomy and anthropometry

The human anatomy inherently affects both speed and accuracy in performing various types of movements. Huchingson (1) points out that human joints have a limited range of movement and, in conjunction with limb length, they limit the maximum reach capability. With tasks that require repetitive lifting motions or lifting heavy objects from awkward positions, localized muscle fatigue limits strength and endurance. Flexibility of movement and posture is limited by the construction of the skeleton, that is, the manner in which the bones are connected at the joints. Therefore anatomy constrains our angular movements and reach capabilities.

When designing workspaces and sizing equipment and clothing, physical dimensions of the body are a critical factor. Because humans are constructed in a variety of shapes and sizes (tall/short, strong/weak, heavy/slim, old/young, male/female, etc.), it is difficult to quantify the *average* person. Engineers face a significant challenge in designing each piece of equipment so that it can be operated and maintained by any user that might be expected to work within that particular system.

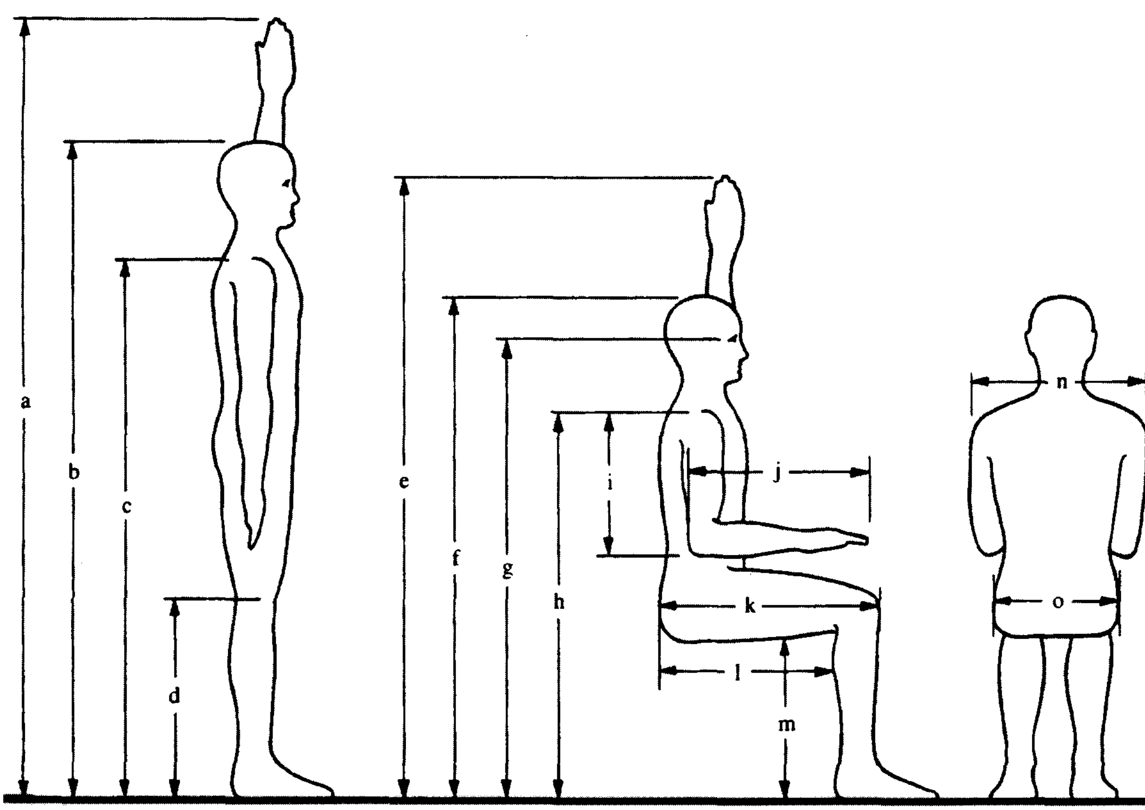
Anthropometry is the study of the size and proportions of the human body. Anthropometric data is usually presented as 5th, 50th, and 95th percentile values, and systems are generally designed to accommodate those values occurring between the 5th and the 95th percentile. For example, when determining the amount of force necessary to operate a particular device, it must be operable at the 5th percentile value to allow the smallest user to generate an adequate amount offorce. Similarly, when considering clearances for openings or passages, the 95th percentile value must be used as the minimum limiting value to allow passage for the largest user.

As illustrated by Figure 15.3, anthropometric data comprehensively includes all dimensions and range of movement capabilities of human beings. For instance, a joint's range of motion is measured between the two extreme positions and is expressed in total angular degrees, or angular degrees from a null position before forming the angle. It's important to note that if the data were given in linear measures rather than degrees, subject variations in trunk and limb length would affect the maximum capabilities (1).

Percentiles.

	Male			Female		
	5th	**95th**	**1st to 99th**	**5th**	**95th**	**1st to 99th**
a.	82.0(209.1)*	93.1(236.6)	80.2-95.9(203.6-243.4)			
b.	64.3(163.4)	73.0(185.4)	62.8-74.5(159.6-188.2)	60.0(152.4)	67.8(172.2)	58.5-69.5(148.6-176.6)
c.	52.8(134.0)	60.8(154.5)	51.2-62.4(130.1-158.4)	49.3(125.2)	56.4(143.4)	47.9-58.1(121.7-147.5)
d.	18.8(47.6)	23.1(58.8)	18.1-24.1(45.9-61.3)			
e.	50.4(128.0)	58.1(147.5)	48.9-60.2(124.1-152.8)			
f.	33.0(83.7)	38.1(96.7)	32.0-39.2(81.4-99.6)	30.9(78.4)	35.0(88.9)	30.0-35.9(76.2-91.1)
g.	28.3(71.9)	33.2(84.3)	27.4-34.4(69.5-87.4)			
h.	22.3(56.7)	26.8(68.2)	21.2-27-9(54.0-70.8)			
i.	13.4(33.9)	15.9(40.4)	12.7-16.3(32.2-41.4)	11.9(30.2)	14.3(36.2)	11.3-14.8(28.8-37.6)
j.	17.4(44.1)	20.6(52.3)	16.6-21.4(42.1-54.4)	15.3(38.9)	18.0(45.7)	14.7-18.7(37.3-47.4)
k.	21.7(55.0)	25.6(65.0)	20.9-26.6(53.1-67.6)	20.5(52.0)	24.3(61.7)	19.7-25.3(50.0-64.3)
l.	18.2(46.2)	21.4(54.4)	17.6-22.3(44.8-56.7)			
m.	16.1(40.8)	19.2(48.8)	15.5-19.8(39.4-50.3)			
n.	17.0(43.2)	20.3(51.6)	16.5-21.0(41.8-53.5)	14.1(34.9)	17.4(44.2)	13.5-18.4(34.2-46.7)
o.	13.2(33.5)	16.7(42.4)	12.6-17.5(32.1-44.5)	12.9(32.7)	16.5(42.0)	12.3-17.7(31.1-44.9)

*Inches (centimeters).



a- Standing Vertical Reach
b- Standing Height
c- Shoulder Height
d- Kneecap Height
e- Sitting Vertical Arm Reach
f- Sitting Height
g- Eye Sitting Height
h- Mid-Shoulder Sitting Height
i- Shoulder-Elbow Length
j- Elbow-Fingertip Length
k- Buttock-Knee Length
l- Buttock-Popliteal Length
m- Popliteal Height
n- Shoulder Breadth
o- Hip Breadth, Sitting

Figure 15.3 Selected Anthropometric Measurements (U.S. Army Population)

Although most U.S. anthropometric design data is compiled from and refers to military populations, various attempts have been made by commercial and civilian firms to estimate body dimensions of the current U.S. civilian population. One such estimate is presented in the Handbook of Human Factors (10). Military anthropometric data is presented in the American Society for Testing and Materials (ASTM) Standard F 1156 (11).

Human body dimensions vary with age, sex, race or ethnic group and occupation, and it is essential that the particular user population be defined before referring to anthropometric. An additional factor to consider when selecting anthropometric data is that body dimensions change from generation to generation, therefore requiring ascertaining the applicable publication date of the reference data (2). Finally, depending on the particular system to be designed, it is often possible to predict the type of user operating the system, which in turn points the designer to the most relevant data source to use.

Huchingson (1) presents a useful guide, step by step, of the proper stages to conduct when using anthropometric data. The first step is to determine the relevant dimension for the problem. For example, the maximum distance a person can reach to operate an overhead control knob while seated at a workstation, or the minimum sized hatch opening for an emergency egress from a machinery space.

Second, it is necessary to determine the user population for the particular system in question. For instance, an older population would be expected on a cruise ship, whereas a younger, fit population would be expected on a naval warship. The third step is to select the range of users to be accommodated (typically this is 5th percentile female to 95th percentile male). This range is only presented as guidance and is typically used because of its cost-benefit relationship.

In other words, including a larger range of users significantly increases the cost without an adequate increase in benefit.

The fourth step is to extract the percentile date from the appropriate anthropometry table, ensuring that it is applicable by population type and date of publication (select references are provided at the conclusion of the chapter). Finally, corrections should be added or subtracted, if needed, for clothing and posture restrictions.

15.3.2.2 Work and strength characteristics

Coincidental to the many shapes and sizes of humans, the amount of work and force a human can generate is also widely varied. Strength and lifting capacity can be classified as either *dynamic* or *static* force. According to Burgess (2), lifting and force capabilities are biomechanically limited by the torquing forces applied at articulation points, and the counterbalancing of body-member weights applied against the load or resistance force. The lumbar spine (lower back) and the torquing forces applied to it also largely limit humans' lifting capabilities. Those factors that primarily influence maximum static arm force are the plane in which the force is exerted relative to the body, the direction of the force, and the degree of arm extension.

Additional generalized human strength characteristics are that people are much stronger in pushing and pulling motions than in either up/down or in/out directions (Figure 15.4).

Other factors influencing strength include posture (seated is better than prone), the bracing of a person's back and feet, the seat back angle, and distance from midsagittal plane, or midline (1). Huchingson (1) also points out that weight lifting studies show other important factors to be the distance between the weight and the floor (best when between the hip and shoulder), the dimensions of the container (compact is best), and the distance of the moment from the center of gravity of the body (close to the body is best).

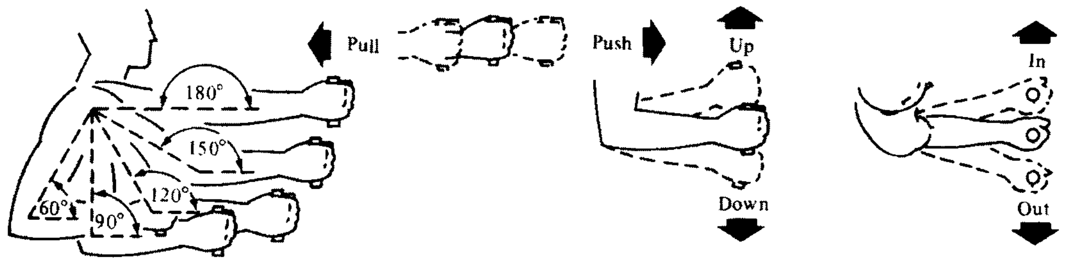
A final concept relating to human physical capabilities is that of the energy cost of work. The maximum force limits outlined above apply to one-time, high effort tasks; however, during repetitive-type work in which the operator is required to conduct the same task several times per day a different measure is required. Work physiologists work within human factors to determine the energetic effects of typical work and the demands it imposes on the worker.

Davis, et al (12) observes that there is no single measurement technique that can be used to measure the effects of all types of loads on an individual. For example, in some cases, measures of physiological response (heart rate, oxygen consumption, blood pressure) may be appropriate while in others, a secondary loading task or visual acuity test may be better. Motion economy principles, when employed during the design process, help to reduce movement and effort, improve efficiency, and reduce costs. These principles should also be applied to workplace design, fatigue reduction, safety engineering practices, and workplace ergonomICS.

The following motion economy principles are provided by Huchingson (1):

- use two-handed operations that are symmetrical and simultaneously away from or toward the body,
- use a motion that uses few stops; ballistic movements are faster and more easily carried out than slow, controlled ones. Continuous, curved motions are preferred to straight-line motions with abrupt changes in direction,

Arm strength*



Elbow flexion	Push		Pull		Up		Down		In		Out	
	R	L	R	L	R	L	R	L	R	L	R	L
Seated (in pounds)												
180°	50	42	52	50	14	9	17	13	20	13	14	8
150°	42	30	56	42	18	15	20	18	20	15	15	8
120°	36	26	42	34	24	17	26	21	22	20	15	10
90°	36	22	37	32	20	17	26	21	18	16	16	10
60°	34	22	24	26	20	15	20	18	20	17	17	12
Prone (in pounds)												
180°	31	26	31	18	8	5	13	7	12	10	9	4
150°	29	24	29	21	13	7	15	10	15	8	12	5
120°	29	21	31	22	13	11	15	11	15	9	11	6
90°	26	18	24	23	15	15	16	12	16	13	13	6
60°	24	17	21	17	13	13	13	10	16	11	12	8

Figure 15.4 Design Values for Maximum Force (1)

- keep elbows close to the body. Finger motion conserves energy more than arm and body motion. Use limbs and digits that are most appropriate for the task and arrange work to permit an easy and natural rhythm,
- provide fixtures to hold parts so that hands are not wasted as a holding device, that is, avoid static work,
- eliminate unnecessary movements by employing gravity or mechanical devices as in drop-delivery of work items or belt conveyors,
- arrange workspaces as much as possible so that a movement does not have to be made against the force of gravity,
- arrange parts for easy access without long arm reaches or movement,
- preposition tools and materials to eliminate searching and selecting,
- alternate sitting and standing if possible,
- arrange the height of the workplace and seat to provide for the comfort of the worker; arrange the workplace so that the visual work items are close and so that frequently used controls are accessible,
- provide for safety and comfort in the environment,
- schedule work pauses to reduce fatigue and eliminate boredom, and
- promote orderliness and cleanliness.

A complicating issue in the design of ships with respect to the energy cost of work is that the very environment in which the work is conducted *moves.* Ship motions influence a crew's ability to conduct their prescribed duties in a number of ways. Wertheim has classified the impediments to performance based on their actions on individuals and he differentiates between *general* and *specific* effects of a given motion.

General effects refer to any task or performance carried out in a moving environment. These effects influence a person's motivation levels (motion sickness), their overall energy levels (motion-induced fatigue caused by added muscular effort to maintain balance), or biomechanically limit their ability to conduct their job (interference with task performance due to loss of balance).

Specific effects are defined ::isthose that interfere with specific human abilities such as cognition or perception (13). Suffice it to say that these effects all combine to make a given task more difficult than the same task conducted ashore in a stationary environment. For a more thorough discussion of the performance implications of ship motions, refer to Stevens (14).

15.4 Human Sensory Limitations

In the previous sections, various physiological and cognitive human capabilities and limitations were discussed. The reader will note that several senses were not discussed, specifically vision, hearing, and temperature control. Although these senses are both cognitive and physical in nature and could have been appropriately discussed in the preceding sections, they warrant a more comprehensive discussion addressing relevant design issues (lighting, noise, general arrangements, etc.) *in concert* with the respective human sensory function.

15.4.1 Illumination and Vision

Vision is usually considered one of the stronger human capabilities and accounts for as much as 70% of humans' information acquisition. In general, the visual modality is comprised of the following distinct characteristics, described by Huchingson (1): intensity detection,

- frequency detection,
- discrimination,
- acuity,
- field of view,
- visual search, and
- distance/speed/acceleration estimation.

15.4.1.1 Characteristics of vision modality

Intensity detection refers to the minimum amount of electromagnetic energy necessary for human detection of light. Light sensitivity is influenced by many factors including age of the individual, duration of light exposure, contrast of light with the background, and the specific region of the retina stimulated. The retina of the eye is composed of specialized receptor cells called rods and cones, thus named because of their shape. Rods are more abundant in the periphery of the retina and are responsible for black/white and night vision, while cones are centralized around the fovea (focal point) of the retina and are used for color and daytime vision.

Frequency detection concerns the humans' sensitivity to wavelengths between approximately 380 and 760 nanometers. This covers the spectrum of violet on the shorter wavelength to orange and red on the longer wavelengths. It generally takes about 30 minutes for the eyes to completely adapt from daytime to nighttime vision. Table 15.1also summarizes the range of sensitivities of the visual sensory modality.

Discrimination is the ability of a person to differentiate a stimulus, either relatively or absolutely. Relative discrimination involves comparative judgments with sensed physical standards, whereas absolute discrimination is based upon pure recall with no standards other than past experience as a guide to estimation. Many more relative than absolute discriminations are possible. For example 570 differences in white light brightness are recognizable when the person can *compare* the lights simultaneously, while only 3 to 5 brightness's can be differentiated on an absolute basis when the lights are presented one at a time.

Acuity is the ability to resolve details. The lens of the eye is responsible for focusing images on the retina of the eye; however, lens shape abnormalities cause such vision problems as near- and far-sightedness and astigmatism. *Field of view* is about 130 degrees vertically and 208 degrees horizontally, assuming the neck to be stationary and the eyes to be fixated straight ahead. The field of color vision is restricted within this overall field due to the eye's physiological makeup as discussed above. Obviously, neck and eye movements increase the field of view accordingly.

Visual search has to do with humans' ability to recognize a target sighted with fovial vision several times smaller than a target sighted with peripheral vision. This is a characteristic of the eye's tendency to successively fixate on different points in an area at a rate of three points per second. This fixation time is a useful measure for establishing the conspicuity or targets.

Distance, speed, and acceleration estimation is our ability to estimate these quantities in absolute terms. According to Grether and Baker (15), without familiar objects to reference these values, humans are generally not very proficient at determining distance, speed, or acceleration in absolute terms. However, humans generally develop skill in estimating relative speeds, for example, a skilled baseball hitter knows when to swing the bat even though the hitter would find it difficult to determine the exact speed of the ball (1).

Designing systems that account for the human's visual abilities entails providing lighting systems that are compatible with the diverse seeingneeds of humans. This in-

TABLE 15.l Human Sensory Modalities and Ranges of Sensitivity (2)

Modality	*Energy Classification*	*Range of Sensitivity*	*Peak Sensitivity*
Auditory	Rapid pressure oscillations in a transmitting medium	20 to 20,000 cycles per second at an intensity of 0.001 to 1000 dynes per square centimeter	500 to 5,000 cycles per second
Visual	Wavelengths of light	400 to 760 millimicrons at intensities from 10^{-10} to 10^4 foot candles	520 to 620 millimicrons
Skin Pressure	Physical imprint of structural indentation on the skin surface.	Two milligrams of soft-point pressure on the skin. Pain erupts w/ hard sharp points at around 2 grams of pressure.	Occurs at areas with the greatest number of pressure points—fingers, palms, tongue, etc.
Skin Temperature	Physical/structural contact with skin surface having varying degrees of temperature.	4°C to 50°C. Pain occurs beyond these levels.	3°C to 12°C for "cold." 45°C to 50°C for "hot."
Smell	Gaseous molecular structure.	One 460-millionth of a milligram. Odor fades rapidly with increasing amounts.	First 3 to 4 minutes after odor detection.

volves considering sources of illumination, the technology of the particular luminary design and its placement, reflection from surfaces, glare reduction methods, and the intensity of illumination required for particular tasks. Other qualitative factors to bear in mind are glare control and brightness contrast, and the control of direction, distribution, diffusion, and uniformity of the light source. Huchingson (1) notes that improperly designed lighting systems may contribute to eye fatigue, increased errors, and increased accident rates.

Ideally, some type of natural lighting should be incorporated into the design wherever possible. However, as in most systems, this is simply not always feasible. Artificial lighting is most prevalent, especially within the confines of the ship, where natural lighting is impossible to attain. Artificiallighting varies from totally direct to totally indirect. Direct lighting is most efficient in terms of output per electrical power, but it also has the problems of glare, contrast, and shadows. Conversely, indirect lighting provides a more even distribution of illumination, but requires more electric power for the same amount of illumination.

Various levels of light intensity are required to perform specific perceptual motor skills. For instance, when speed and reading accuracy are required, high visual contrast is necessary; when sharp vision is necessary, blue colored illuminants should be avoided. The following is a brief set of suggestions to incorporate into the design of lighting (1):

- use indirect lighting when possible,
- install polarized shields to prevent glare,
- install multiple small lights rather than a few bright ones to control glare intensity, and
- use non-reflective surfaces with less than 30% reflecting values for floors, equipment, and work surfaces.

15.4.1.2 Lighting and human performance

More than simply providing illumination for the environment, lighting characteristics have a profound effect on humans' biological clocks and sleep cycles. Light is an integral part of the human body's biological clock or, in other words, it is a determining factor in how the body regulates its circadian rhythms. Obviously, sunlight was originally intended to cycle the human's biological circadian clock; however with the advent of electricity, electric lighting has become the primary regulator.

On a ship, the majority of the crew spends their day below deck where electric lighting is all that is available. This is problematic and usually creates an irregular and frequently changing sleep cycle that can easily lead to fatigue. Additionally, the 24-hour schedules of shipboard operators frequently change and individuals work under incandescent or fluorescent lighting throughout the night. Shipboard lighting is generally not sufficient to stimulate the human's biological clock, and as a result, fatigue becomes a significant issue during the early morning hours.

There are ways to adapt humans to working at night and advances in lighting technology have been successfully used in many 24-hour operations to shift circadian rhythms and improve alertness. Currently, the United States Coast Guard is developing a commercials maritime Crew Endurance Management Program that uses improved lighting (only one of many shipboard environmental improvements) in conjunction with a well-planned and implemented endurance management program.

15.4.1.3 Advances in lighting

Lighting has greatly improved over the years. Higher intensity bulbs are more readily available as well as improved lighting spectrums. Some current studies are also looking at low level monochromatic lighting that can be used to shift the human biological clock.

One example of a lighting advancement that is commercially available is referred to as Circadian Lighting Systems. These systems have made it possible to alter the biological clock so that watch standers remain alert at night and sleep well during the day. Circadian lighting systems come in many forms, ranging from a single set of lamps measuring 600 by 1000 m to whole-room systems. These systems have variable light outputs under either manual or computer control. The computer-controlled systems track each worker's shift schedules and can make changes accordingly. The high light output (-10 000 lux) is 10 000 times greater than any level suggested by current maritime standards.

In most shipboard applications 10 000 lux is too bright and lower levels must be used. This is mainly due to the low overhead heights. The bulbs are too close to the eyes and can become very annoying. However, it is also sufficient to increase illumination levels to something more reasonable (-1000 lux). These systems are ideally placed in strategic areas such as the engine control room. High intensity lighting systems are recommended in areas where crewmembers work and relax, for example, berthing areas, passageways, recreation rooms, and office spaces. Though these systems are initially expensive, the long-term fatigue-mitigating effects greatly improve crew well-being and safety.

A comparison of some typical illumination levels for various conditions are provided in Table 15.11.

High intensity lighting has been used successfully to alter individuals' sleep cycles. Research indicates that light has a greater effect on the human biological clock than previously believed.

Recent studies have also shown that the quantity of light required to affect this clock is much less than previously theorized.

Researchers at Harvard Medical School discovered that a *clock resetting* effect could be accomplished, even at illumination levels 20 times less than daylight. Adjustments to the natural circadian rhythm as much as one-hour were attained with as little as three days of five-hour exposures per day.

In order to effectively implement human factors into the design of lighting systems, the designer needs to account for these human performance issues. Current lighting guidelines and standards issued by class societies are specifically *task* oriented. In other words, the suggested illumination levels for various areas are based on task performance and energy consumption not particularly on human health and well-being. Although natural sunlight has the most profound effect on the body clock and a person's health and well-being, full spectrum higher intensity artificial lighting has been found to have positive effects on fatigued operators and to increase human performance and should be strategically located throughout a ship.

15.4.2 Noise and Hearing

Hearing is regarded as the second most used sense. From a mechanical perspective, the hearing mechanism responds to rapidly oscillating air, solids, or liquid mediums that are excited by a sounding body (1). Forces and frequencies outside humans' auditory limits are either not detectable, or can be painful and damaging to the hearing mechanism. The binaural structure of the ear is also limited in its directional sensitivity, being most easily confused from the front and rear, and above and below. Table 15.1, included earlier in this chapter, provides the range of, and peak sensitivities of the auditory modality.

Noise is basically defined as unwanted or undesirable sound. It is present in most compartments of a ship and it is virtually impossible to escape from. Noise comes from countless sources including engines, generators, pumps, air

TABLE 15.II Typical Illumination Levels for Various Conditions

Typical Range (Lux)	*Condition*
100 000	Bright sunny day
10 000	Cloudy day
1000–2000	Watch repairman's bench
100–1000	Typical office
200–1000	Night sports field
1–10	Residential street lighting
0.25	Cloudy moonlight

conditioners, and other marine equipment. There are a number of human physiological and physical impacts of noise in the work environment and they all negatively affect human performance and cause fatigue.

Noise characteristics can be defined as either impulse or steady state. Steady state machinery noise may be classified as the continuous, as in the steady drone of a piece of equipment. Impulse noise may be periodic as in the operation of a pneumatic drill or of an impact nature as in a drop forge or the firing of a weapon. Impulse noise is measured as a sound pressure level by frequency or Hertz, with duration and annoyance factors indicated. Conversely, steady-state noise is constant and is measured in terms of potential hearing impairment dangers and levels of discomfort, speech interference, and performance degradation. Excessive noise can easily cause short term (recovery in a few days), and even permanent, hearing loss. Noise levels exceeding 120 dB in the octave bands between 300-600 Hz can lead to discomfort in few seconds and levels that exceed 136-140 dB are quite painful (1). Table 15.111 is presented to summarize general guidelines for human noise tolerance and safety levels.

15.4.2.1 Noise and performance

Noise does not have to be extreme or damaging to induce performance degradations. As Huchingson (1) observes, noise can also be a source of annoyance in instances where the noise level is well below exposure limits, but creates annoying effects and degrades concentration.

Though these physiological effects are less perceptible than those described above, they can have a tremendous impact on human performance via noise induced fatigue. Bost (6) presents a useful table illustrating the performance characteristics of humans in response to varying levels of noise (Table 15.1V).

Guidance on noise levels is available but focuses on the prevention of hearing damage from high intensity noise. However, low intensity noise must be considered because it also affects human performance and can severely affect sleep. The designer concerned with human factors in the shipboard environment should therefore address the physiological effects of lower intensity noise.

These physiological effects are the result of the human *body'sfight or flight* response. The body perceives noise as a threat or warning of danger and continuously responds, even at low noise levels and while a person is asleep. Although most noise is not a sign of impending danger, the body continues to interpret it as such.

Typically the blood pressure rises along with the heart and breathing rates, metabolism accelerates, and a low-level muscular tension takes over the body. If the noise continues for longer periods of time, the factors begin to compound and relaxation becomes increasingly difficult. Even when a person is sleeping, these changes occur, impairing the body's ability to recharge and resulting in fatigue.

TABLE 15.III Noise Level and Performance Degradation (2)

Noise Level (dB)	*Performance Degradation/ Hearing Protection Required*
110–130 dB	Cannot communicate; protection needed
100–121 dB	Only earphone communication possible; protection needed
86–110 dB	Loud shouting necessary; protection needed
81–106 dB	Raised voice necessary; discomfort experienced
65–75 dB	Normal voice up to five feet away

When the noise exposure is long-term, the human body is kept in a constant state of agitation and the physiological responses continue to occur even ifthe noise is not perceived as aggravating. It has been suggested that these responses build upon one another, leading to what is referred to *as diseases of adaptation.*

Some of the diseases include asthma and high blood pressure. A more complete list follows:

- neuropsychological disturbances (headaches, fatigue, insomnia, irritability, neuroticism),
- cardiovascular system disturbances (hypertension, hypotension, cardiac disease),
- digestive disorders (ulcers, colitis),
- endocrine and biochemical disorders, and
- sleep disturbance.

The level of noise that causes the human body to respond varies from person to person. Mariners working in a noisy environment often experience moodiness, irritability, increased stress, inability to effectively deal with minor frustrations, and impaired decision-making abilities. Noise also affects the sleep patterns of shipboard personnel, significantly contributing to fatigue. Noise makes it difficult to fall asleep, can wake a person throughout the night, and pulls a person from deeper to lighter sleep stages. Nightly interruptions can become so frequent that someone may begin to forget that they were even awoken and return to sleep more quickly. This pattern is particularly dangerous because the person is getting insufficient sleep and will be drowsy the next day.

TABLE 15.1V Noise levels and Human Performance (6)

Noise Level, dB	*Peiformance Effects*
100	Serious reduction in alertness. Attention lapses occur. Temporary hearing loss occurs.
95	Upper acceptance level for occupied areas. Temporary hearing loss often occurs. Speech extremely difficult, and people required to shout.
90	Half of the people judge the environment as being too noisy. Some momentary hearing loss occurs. Skill errors and mental decrements will be frequent. Annoyance factor high, and certain physiological changes often occur (for example, blood pressure increases.)
85	Upper acceptance level in range from 150 to 1200 Hz. Some hearing loss occurs. Considered upper comfort level. Some cognitive performance decrement can be expected, especially where decision-making is necessary.
80	Conversation is difficult. Difficult to think clearly after about 1 hour. May be some stomach contraction and an increase in metabolic rate. Strong complaints can be expected from those exposed to this level in confined spaces.
75	Too noisy for adequate telephone conversation. A raised voice is required for conversations two feet apart. Most people judge the environment as too noisy.
70	Upper level for normal conversation. Unprotected telephone conversation difficult.
65	Acceptance level for a generally noisy environment. Intermittent personal conversation acceptable. Half of the people will experience difficulty sleeping.
60	Upper limit for spaces used for dining, social conversation, and sedentary recreational activities.
55	Upper acceptance level for quiet spaces. Raised voices required to converse over distance greater than 8 feet.
50	Acceptable to most people where quiet is expected. About 25% will be awakened or delayed in falling asleep, Normal conversation is possible at distance up to 8 feet.
40	Very acceptable to all. Recommended upper level for quiet living spaces.

The levels at which sleep disturbance can occur are typically lower than guidelines acknowledge. Studies have shown that noise levels as low as 40 to 50 dBA (lower than a casual conversation) have increased the time to fall asleep by as much as one hour. As the sound levels increased, increasing numbers of subjects had difficulty falling asleep. These studies have also shown that 70 dBA is enough to change the sleep patterns of most subjects. It should also be noted that noise *duration* also affected sleep, for example, short signals tended to awaken more subjects than a long and steady noise.

Unfortunately, examples of poorly designed general arrangements abound in which sleeping quarters are placed under flight decks, over and adjacent to major machinery spaces, and along high traffic passageways. Although it can be challenging to design general arrangements that reduce noise levels in sleeping quarters, proper placement of sleeping quarters and crew recreation compartments is critical to crew performance.

15.4.2.2 Noise reduction

Noise reduction management is a significant criterion in the design of any ship. In order to reduce shipboard noise and the associated problems, designers must have a clear understanding of what noise is and how to reduce its effects. Audible noise categorized into two classes, airborne and structure-borne.

Airborne noise is what causes stress and hearing loss, whereas structure-borne noise causes damage to machinery and marine structures.

A discussion by Huchingson (1) indicates that there are three different methods of reducing and minimizing the effects of noise: source control, path control, and receiver control.

- *Source Control:* Sources of noise occur from vibration, impact, friction, and turbulence. Vibrating machinery noise may be reduced by techniques such as balancing rotating parts, using rubber mountings, employing surface damping, tightening loose parts, reducing speeds, and avoiding resonance frequencies. Impact noises should be eliminated where possible; however, if the equipment or process cannot be modified in such a way, the noise may be reduced by using resilient materials and proper lubrication, enclosing the impact area, or reducing the forces that are used. Friction noise can be reduced by lubrication and by providing smooth contact surfaces, rolling contact, precision gears, etc. Finally, turbulence noise from pipes and ducts may be reduced by streamlining the flow within the piping and ducts, removing obstacles to flow, lining air ducts, sizing the valves properly, and reducing velocities of flow.

- *Path Control:* Between the source and the receiver, the noise must travel through a transmitting medium. In path control, this medium is altered to reduce spreading noise. This might involve increasing the distance between the source and listeners, enclosing the source in a sealed compartment or using intervening structures, or using baffles, mufflers, and absorbing materials to channel the nOise away.
- *Receiver Control:* The receiver (human) always has the option of using hearing protection. This is by far the most uncomplicated method of controlling noise, but not always the most effective. First of all, it relies on the user's discretion and sensibility to wear the hearing protection, and secondly it does not address the underlying problem of the noise in the first place.

Although noise is an unavoidable issue in ship operations, steps can be taken in the design stages to decrease its effects. Post-production measures can also be taken to reduce noise levels and increase the quality of life for the human operators. The current standards for noise exposure are acceptable for decreasing the chances of permanent hearing damage but are inadequate for protection against subtle physiological effects oflong-term low intensity noise exposure.

15.4.3 Guidelines for Visual and Audio Displays

It naturally follows from the preceding discussions that the human operator is responsible for a multitude of information arriving from the auditory and visual sensory modalities. Audio and visual displays must therefore be carefully designed and thoroughly reviewed.

When determining the need for a display, the designer must first determine the function and nature of the display. This is a widely varied science which cannot be fully presented here; however, a basic understanding of these concepts will help to point designers in the right direction and ask the right questions. Grether and Baker (15) discuss five distinct functions of displays, listed as follows:

- continuous system control (tracking/steering a vehicle),
- monitoring systems status (warning light for engine parameters),
- briefings (maintenance checkout sequence),
- search and identifications (pattern recognition in recognizing targets on photographic or radar displays), and
- decision making (trouble shooting malfunctioning equipment).

Huchingson (1) also presents several guidelines for constructing visual displays. These are listed as follows:

- *Content:* The information displayed should be limited to what is necessary to perform specific actions or make decisions.
- *Precision:* Information should be displayed only to preCISIonnecessary.
- *Format:* The information should be in directly usable form, that is, no transposition, computation, interpolation, or translation into other units should be required. The format of a display may be either analog or digital: in general, humans process analog displays more effectively for most processing and monitoring functions, while digital displays are more effective when precise information is required.
- *Redundancy:* Displayed information should not be repeated unless it is necessary for reliability.
- *Failure:* Any breakdown or malfunction of a display or display circuit should be immediately apparent.
- *Unrelated information:* Information such as trademarks should not be displayed on a panel face.

Auditory information is most often conveyed via alarms and is most effective for use in warning situations or where multiple visual inputs overburden the information processing abilities of humans. Auditory information is also more rapidly conveyed than the visual information since the ears are omnidirectional. According to Huchingson (1), auditory information permits operators to detect the presence or absence of a signal or an alarm state, to discriminate two or more signals, or to identify the class of a particular signal. Usually, auditory displays should be used to relay one-dimensional information since the retention of long and complex auditory messages is difficult unless the message is repeated several times. Table 15.V is provided to summarize the criteria used to determine when each of the display types is more appropriate.

Alarms are the most prevalent type of auditory display and must be selected based upon their relative ability to attract attention and to penetrate noise. These characteristics are based upon the intensity, frequency, periodicity, and phase differences of the noise, as well as the type of background noise and its masking effects. For instance, some alarms are intended for outdoor use or transmission through barriers while others are suited for indoor used when background noise is at a minimum.

McCormick (16) has outlined a set of auditory display principles that are presented here:

- *Compatibility:* Encoding signals should exploit population stereotypes such as increasing pitch to suggest higher altitude, or a wailing sound to suggest emergency. Newly installed signals should be carefully designed so that they do not conflict with previously learned signals.

TABLE 15.V Guide to the Use of Auditory and Visual Display (1)

Use auditory displays when the ...

- message is simple and short
- message calls for immediate action
- message will not be referred to later
- message deals with events in time
- operator's visual system is already overloaded
- illumination limits vision
- job requires moving about frequently
- stimulus is acoustical in nature

Use visual displays when the ...

- message is long and complex
- message does not require quick action
- message will be referred to later
- message deals with locations in space
- operator's auditory system is overloaded
- location is too noisy
- job permits operator to remain in one position
- stimulus is visual in nature

- *Approximation:* This refers to using a signal to attract attention, and then employing another signal for more precise information.
- *Dissociability:* This refers to the use of signals that are highly discemable from ongoing audio input, for example, do not use bells when other bells are ringing often.
- *Parsimony:* This suggests limiting input signals to just those that are necessary.
- *lnvariance:* This refers to standardization of signal meanmg.

15.5 SHIP MOTIONS: VIBRATIONS AND ACCELERATION

The vibrations below the audible range, between 1 and 100 Hz, are those vibrations generally caused by operating machinery that are transmitted through structural components of the ship directly to whole-body surfaces or to particular parts of the body such as the head or limbs. These vibrations have physiological implications when they are transmitted through supporting surfaces to parts of the body such as the buttocks and feet, but also visual implications when they vibrate instruments or panels that to the point of impairing visual performance.

Huchingson (1) indicates that the parameters of vibration to be considered are frequency (rate of oscillations), amplitude (maximum magnitude of cyclic displacement), and acceleration (second derivative of displacement). It is also noted that, as with other environmental stresses, there are proficiency limits, comfort limits, and health and safety limits.

Mariners experience shipboard vibrations that are caused by machinery, marine equipment and the ship's response to the seaway. The vibration resonant throughout the hull structure and the entire crew is continuously affected. The propagation of these vibrations along the decks and bulkheads subject the crew to whole body vibration and noise. Short-term exposure can lead to headaches, stress, and fatigue. Long-term exposure can eventually lead to hearing loss and constant body agitation. The current vibration guidelines do keep vibrations to safe levels but do not give enough consideration to human fatigue and stress.

The effects of whole body vibration are well studied and documented. There are a number of ill effects of vibration on the human body. Some of these effects are long term, such as musculoskeletal injuries, back disorders, and bone degeneration. These problems are typically avoided if designers follow the established acceptable vibration guidelines. An example of these guidelines is shown in Figure 15.4.

There are more serious effects that occur from whole body vibration and these are the ones that most operators are confronted with. These effects are more serious because they cause physiological changes that lead to fatigue and a decrease in human performance. Below is a list of these effects:

Physiological:

- cardiac rhythm increases,
- respiration rhythm increases,
- blood circulation increases,
- vasoconstriction,
- endocrine secretions, and
- central nervous system affected.

Comfort and Peiformance:

- pam,
- nausea,
- vision problems,
- posture,
- movement and coordination decline,

- force, and
- perceptions altered.

Figure 15.5 illustrates the vibration frequencies at which typical side effects occur.

Many effects noted in the previous paragraphs can go unnoticed and are sometimes imperceptible to the operator. They also occur at much lower vibration levels than those currently treated as problematic. Many of the larger vibrations created by engines, generators, and pumps can be reduced through damping and isolation.

Just as sound vibrations can be reduced and controlled, discussed in Sub-section 15.4.2.2, whole body vibrations can be similarly controlled:

- *Source Control-Reduce* vibration intensity, avoid resonance.
- *Path Control-Limit* exposure time, reduce vibration transmission (structural dampening), use vibration isolators.
- *Receiver Control-Use* vibration isolators, adapt posture, and reduce contact area.

Vibration noise is best treated through the isolation of the machinery from the hull. There are a number of ways to do this including rubber padding to spring or rubber mounts. If the vibration energy cannot be isolated at the source than it should be dissipated along its path by using dampers.

Insulation is used to combat the airborne noise and is designed to perform three functions:

- block noise from escaping the engine room,
- absorb noise in the engine room, and
- dampen the vibration energy in the deck and overhead.

Vibration noise can be reduced and contained by using high density and mass lead sheeting placed between two resilient materials. The resilient materials also absorb much of the noise. Acoustical foam or fiberglass can be used as a decoupler for the lead barrier, as well as being the absorption material.

Absorption is accomplished by dissipating the noise energy as it passes through to the lead and as it is

bounced back towards the noise source. Generally, lead core insulation is used on surfaces behind which people will be, and absorption-only material (no lead) is used on surfaces like hull sides, tanks, bulkheads against a fish hold, etc.

Outside of the engine room there are additional steps that can be taken to control both vibration and noise. Often in smaller ships the dry exhaust piping radiates significant noise, as well as heat. High temperature fiberglass insulation layered with an appropriate outside covering will minimize pipe and muffler shell noise.

One of the largest interior surfaces is the ceilings~and their acoustical importance can be significant. Just as in a house with no furniture, carpets, drapes, etc., noise echoes from one hard wall to another, so does the same echo or reflection take place in a ship that has hard finished walls and overhead. A ceiling, which will absorb interior noise, is definitely superior to one that will simply bounce noise. On the floors, carpets with acoustical underlayment will suppress noise from below, as well as absorb vibration energy that's in the floor.

There are many procedures and materials that can be used to keep noise levels under control in commercial ships. It is important to understand what can be accomplished within a given ship or with a particular noise problem. One solution simply will not apply to all of the problems, hence sound level reduction must be initiated with knowledge of the individual ship and its owner's, operator's or designer's requirements understood. Designers will have to consider the added weight and cost while also understanding the added benefits. It is also necessary to reevaluate the current standards that define acceptable vibration levels, looking more at well being than what is *comfortable.*

15.5.1 Ship Accelerations

Though usually not considered in regard to vibrations, the large-amplitude, low frequency oscillations below 1 Hz are

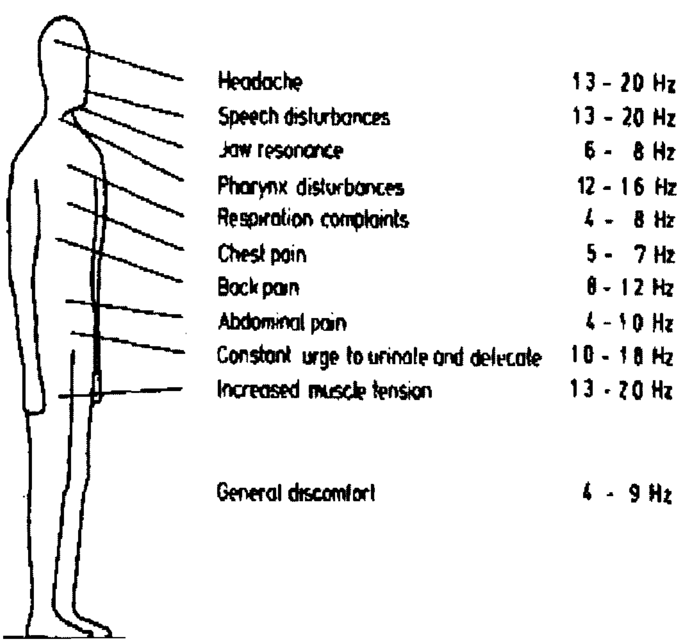


Figure 15.5 Vibration Frequencies and Effects

significant factors affecting human performance. These are the motions due to the hull/sea interaction of the ship (Figure 15.6), and are responsible for a host of physiological, biomechanical, and psychological responses that can severely degrade performance.

Although motion sickness often is accepted as a common element of the maritime environment, and a malaise that one is expected to deal with, it is a debilitating condition that degrades human performance to a significant extent. The motions of a ship at sea induce a variety of physiological and biomechanical events that can quickly reduce even the best of efforts to a fraction of what they would be ashore on a stable platform. Ship motions limit a crews' ability to perform essential command, control, and communications functions, navigation tasks, maintenance responsibilities, and even the preparation of food. Additionally, and more importantly, emergency situations may become more threatening in a situation where only a portion of the crew is able to respond effectively.

Current guidance regarding motion characteristics of ships centers on Motion Sickness Incidence (MSI) rates and Motion Induced Interruption (MIl) rates. MSI is a term developed by McCauley and O'Hanlon (17), which refers to the incidence of vomiting personnel as a percentage of those exposed to motion. Current research continues in this field to determine how to apply this quantity to the design of a ship, but for now it is accepted that the vertical component of motion at a frequency of 0.157 Hz is the most nauseogenic. A Motion Induced Interruption is defined as *an incident where ship motions become sufficiently large to cause a person to slide or lose balance unless they temporarily abandon their allotted task to pay attention to keeping upright.* According to Baitis et al (18) and Crossland and Rich (19), MIls include three distinct phenomena, 1) stumbling due to a momentary loss of postural stability, 2) sliding due to the forces induced by the ship overcoming the frictional forces between moveable objects (for example, the individual's shoes) and the deck, and 3) the very occasional and potentially the most serious conditions where lift-off occurs due to motion forces exceeding the restraining force of gravity.

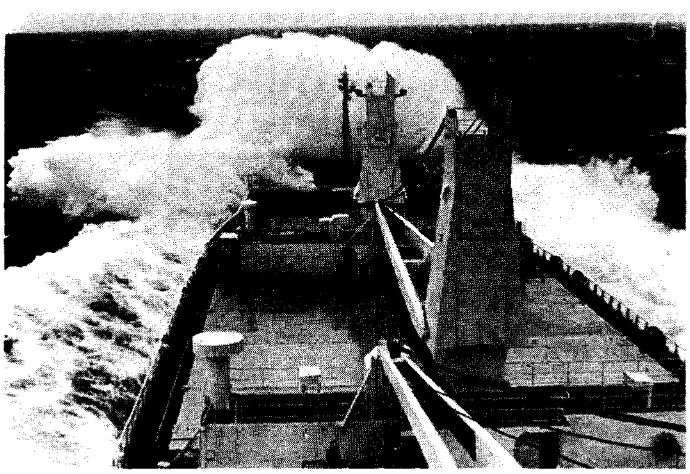


Figure 15.6 MV *Winter Water* takes Heavy Seas on the Bow.

Guidance on MIls is given in terms of a frequency of MIls per unit of time; however, approximating MIls from preliminary hull forms is a difficult task. They are more easily measured within ship motion simulators or field tests, and therefore are a difficult criteria to base design upon. More information on MSI and MIl theory and criteria may be found within Stevens (14).

There are design considerations that may be employed to moderate the effect of ship motions on personnel, or reduce ship motions altogether. Anti-rolling devices and stabilizers such as bilge keels, anti-roll fins, and anti-rolling tanks may be used to reduce the rolling of a ship for crew comfort. Bittner and Guignard (20), in a study of two workstations for the U.S. Coast Guard, recognized five potential engineering approaches to enhance seakeeping through prevention and mitigation of adverse motion effects on personnel as follows:

- *Locate critical stations near the ship's effective center of rotation:* Studies have shown the vertical component of motion to be extremely nauseogenic, and at off center locations on a ship the rotational motion components give rise to substantial vertical displacements. The magnitude of this motion is proportional to the distance from the center of the ship and when combined with the ship's natural heave motion, seasickness frequency can be expected to increase at these off-center locations.
- *Minimize head movements:* Although this may be accomplished through individual behavior, there are also design considerations as well. By locating primary displays and controls on a central panel, the necessity for frequent, rapid, or large-angle head turning may be minimized, thus preventing seasickness (21). Additionally, consideration should be given to methods of stowing tools and other items so that they remain within close reach. For example, picking up a dropped item such as a pen requires large and complex head movements, which may provoke sickness. Work in a ship motion simulator conducted by Wertheim (13) revealed that subjects required to carry out various tasks involving bending down to pick objects up had

higher incidences of seasickness than those who were simply seated.

- *Align operator with a principal axis of the ship's hull:* Because motion sickness is amplified by complex or off-axis angular motion inputs to the vestibular system (inner ear), alignment with the ship's longitudinal axis is preferred over a transverse orientation, and both of these are preferred over diagonal or off-axis orientation.
- *Avoid combining provocative sources:* Current literature indicates that multiple provocative sources tend to be additive. Therefore, a variety of visual distortions can be expected to combine with ship motion to increase the likelihood and severity of seasickness. In terms of design considerations, optimizing the layout of sleeping quarters may improve sleep during rough seas and would be expected to reduce seasickness development. The design of visual display terminals also has important implications in the onset of motion sickness and warrants attention during the design process.
- *Provide an external visual frame of reference:* This has long been recommended as an effective method to counteract the effects and onset of motion sickness. It is a commonly known remedy for seasickness to observe a stable horizon through a porthole or from above decks. Without delving into too much physiology, suffice it to say that conflicting visual and vestibular information is reconciled to some extent by viewing this stable horizon. Since this cannot often be accomplished within the confines of a ship the use of an artificial horizon projected within a workspace has been studied and found to be quite effective. Rolnick et al (22) used a rapidly rotating mirror that moved in synchrony with the ship's pitch and roll movements to project an artificial horizon to the bulkheads of a ship's cabin. They found significant decreases in relative motion sickness and decrements to well being among the 12 subjects used for the study. Studies aboard the M.V. Zeefakkel by Bles et al also implemented an artificial horizon in which a stabilized light was projected to the upper half of a cabin within the ship. It was found that 85% of the seventeen subjects reported the artificial horizon as beneficial to well being.

15.6 OTHER SENSORY AND ENVIRONMENTAL LIMITATIONS

The other sensory modalities that the designer should be aware encompass skin temperature and pressure, and odor. Table 15.1, from Sub-section 15.4.1, listed above summarizes the range of, and peak sensitivities of these senses.

15.6.1 Temperature and Humidity

The human body has the ability to thermoregulate itself in different environments, but this is somewhat limited. Physiological changes such as perspiration, changes in blood flow to skin, shivering, and goose flesh allow the body to adapt to environmental temperature changes. Humans can also regulate temperature through behavioral and environmental changes (1). Behavioral modifications include adding or removing clothes, and resting in warmer temperatures, while exercising in cooler temperatures. Environmental changes can be affected by altering air temperature, humidity, air velocity (for example, fan), and radiation from the sun and other sources.

Because our ability to regulate our own temperature is somewhat limited, a thermoneutral environment is desired. This is the condition in which core temperature is normal and rate of body heat exchange is zero. This set point is affected by several factors including work rate, clothing, and acclimatization (1). The following are some examples of other considerations:

- the band of temperature and humidity that humans can efficiently operate in is relatively narrow,
- surface contact temperatures above 35°C requires that the skin be protected,
- in ambient air temperature over 29°C, performance will deteriorate and optimum performance temperatures in light clothing should be between 21 and 27°C, and
- because evaporative heat loss is severely limited by high relative humidity or moisture in the air, relative humidity within these temperature ranges should be between 30 and 75%, with lower values necessary for comfort in higher temperatures. However, relative humidity lower than 15% can cause excessive skin drying.

Bost (6) presents a useful table (Table 15.VI) outlining the effects of temperature on human performance. Although not generally a significant consideration on ships, wind chill is a separate element of temperature control that needs to be accounted for. Wind chill is the condition in which evaporative heat loss is significantly increased by air velocity. This becomes an especially important issue in cold weather. Ship designers may account for this phenomenon by designing exposed portions of weather decks with adequate protection from wind.

15.6.2 Atmosphere

Related to, but not dependent upon temperature, is the shipboard atmosphere. Adequate supplies of fresh air free of pollutants must be maintained for effective human performance since this has a direct effect on humans' physiol-

TABLE 15.VI Effects of Temperature on Human Performance (61

Effective Temperature (DC)	*Performance Effects*
32	Upper limit for continued occupancy over any reasonable period of time.
27-32	Expect universal complaints, serious mental and psychomotor performance decrement, and physical fatigue.
27	Maximum for acceptable performance even of limited work; work output reduced as much as 40-50%, people experience nasal dryness.
25.5	Regular decrement in psychomotor performance expected; individuals experience difficulty falling asleep and remaining asleep.
24	Clothed subjects experience physical fatigue, become lethargic and sleepy, and feel warm; unclothed subjects consider this temperature optimum without some type of protective cover.
22	Preferred for year-round sedentary activity while wearing light clothing.
21	Midpoint for summer comfort; optimum for demanding visual motor tasks.
20	Midpoint for winter comfort (heavier clothing) and moderate activity, but slight deterioration in kinesthetic response; people begin to feel cool indoors while performing sedentary activities.
19	Midpoint for winter comfort (very heavy clothing), while performing heavy work or vigorous physical activity.
18	Lower limit for acceptable motor coordination; shivering occurs if individual is not extremely engaged in continuous physical activity.
15.5	Hand and finger dexterity deteriorates, limb stiffness begins to occur, and shivering is positive.
13	Hand dexterity is reduced by 50%, strength is materially less, and there is considerable shivering.
10	Extreme stiffness; strength applications accompanied by some pain; lower limit for more than a few minutes.

Note: These temperature effects are based on relatively still air and normal humidity (40-60%). Higher temperatures are acceptable if airflow is increased and humidity is lowered (a shift downward from 1 to 4°), lower temperatures are less acceptable if airflow increases (a shift upward of 1 to 2°).

ogy, health, and well-being. Common air pollutants include carbon monoxide, ammonia, nitrogen oxides and aldehydes. In concentrated doses these can be lethal, causing brain damage, tissue and organ damage, and at the same time, severely degrading human performance. Concentrated odors of a non-pollutant nature are can negatively affect performance and diminish concentration. This is important because odors can be initially detected at very faint molecular levels.

15.6.3 Skin Pressure

Though not of significant concern to the designer, the skin pressure sense is briefly presented for informational purposes. When compared to the magnitude of the stimulation *possible* for the skin, the sensory response is quite minuscule. The skin responds to a pressure stimulus of approximately two milligrams of pressure whereas upper levels of pressure only elicit general sensations of compression or pain.

15.7 FATIGUE

Although not entirely physical or cognitive, fatigue is a performance factor that merits further discussion.

Mariners are exposed to many mental and physical stressors when working in a shipboard environment. These stressors significantly affect their ability to perform their duties and when these stressors are not controlled, the likelihood of human error dramatically increases. Fatigue is one particular factor worthy of its own discussion that greatly impairs performance and causes human error.

Controlling human fatigue in a marine environment is very challenging. In addition to operational management techniques, it requires a concerted effort in shipboard environmental design. Many opportunities exist throughout the design process to ensure that an adequate shipboard environment is created. The naval architect and marine engineer have direct control of these design aspects and must consider them throughout the design process, including areas like lighting, noise reduction, controlling vibration, ship motions, etc.

15.7.1 What Is Fatigue, What Causes It, and Why Is It Important to a Designer?

Fatigue is a widely prevalent condition familiar to most people. However, it is frequently over-simplified to a simple lack of sleep resulting in mental and physical exhaustion. Feeling *fatigued* is not easily defined and different people describe its feelings in many differing terms. For example, some may describe it as an uncontrollable urge to sleep or rest, while others express it as that fog that envelopes the brain at certain times of the day. There are many physiological and psychological causes of fatigue including high workload, stress, harsh environmental conditions, physical condition, poor design, time of day, hours of sustained wakefulness, etc.

Fatigue's involvement in accidents has been implicated in a number of different industries. Major accidents within the transportation industry include the *Exxon Valdez* and *World Prodigy* accidents as well as the DC-8 aircraft crash in Guantanamo Bay, Cuba. Additional examples include Three Mile Island, Bhopal, and Chernobyl. These significant mishaps further emphasize the need for designers to consider the issue of fatigue and how it falls within the human factors concept of ship design.

After realizing that a person can experience decreased levels of alertness, it is important to be aware of how this affects their performance. Fatigue has been attributed to the impairment of mental abilities, inappropriate risk behavior, impaired learning, and decreased logical reasoning and decision-making. It also decreases human physical abilities such as strength, speed, response time, coordination, and balance. Although individuals handle their performance differently, there are commonly exhibited behaviors frequently seen in someone suffering from fatigue. Four types have been recognized by Sirois and Moore- Ede (23) and they are listed as follows, 1) *Automatic Behavior Syndrome* is what is known as "sleeping with your eyes open." It usually occurs at night but can happen when a person is fatigued. This type of behavior causes a person to go into a daze and greatly reduces their ability to recognize danger or deal with emergencies. Ship helmsman and anyone who must remain stationary to perform a task that is not stimulating or does not require high levels of attention most commonly exhibit such behavior, 2) *Micro Sleep* is the most dangerous and scary behavior because the person actually falls asleep for ten to fifteen seconds. Micro sleep is what often causes car accidents and kills people on dangerous job sites, 3) *Sleep Inertia* is that groggy feeling that someone experiences for up to a half-hour after waking up. Managers and Safety Observers must be aware of sleep inertia and should take actions to prevent someone from performing tasks immediately after waking up. This is a very common problem because it always affects someone, whether they are fatigued or not. Waking up from a deep sleep simply requires time in order to become oriented and to raise awareness, and 4) *Chronic Fatigue* is the result of sleep deprivation and also a lowering of the quality sleep needed for one to become refreshed. Behaviors exhibited by someone with chronic fatigue are tiredness, irritability, and mood swings.

It is not necessary within the context of this chapter to present many more specific details of fatigue. However, it is necessary for the designer to understand and incorporate those design considerations previously discussed which moderate the onset of fatigue and promote optimum levels of human performance.

15.8 THE DESIGN OF HUMAN MACHINE ENVIRONMENTS: WHO DOES WHAT AND HOW?

Technology advances at an incredible rate. Modern ships require computer-controlled systems to operate the vastly improved marine equipment and machinery and operating these systems can be complex (Figure 15.7). The engi-

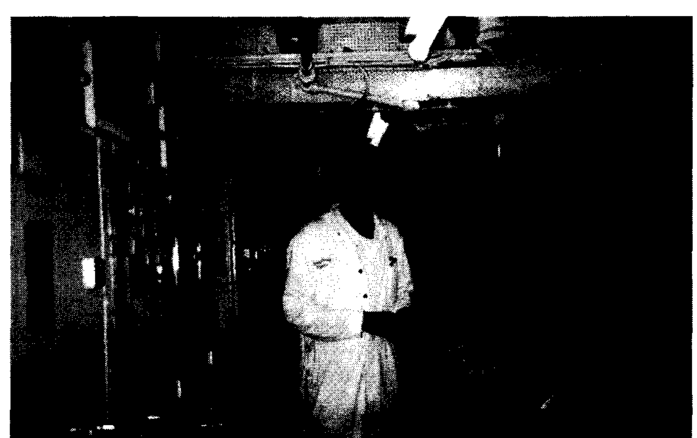


Figure 15.7 Typical Modern Engine Control Room

neering design challenge lies in determining how to most effectively assign job task between computers and human operators.

Using automation and designing Human-Machine (H-M) environments onboard maritime ships poses a unique ship design challenge. Adequate H-M designs allow for reduced manning requirements, but there are safety constraints, mainly due to the unique operational characteristics of ships. A ship is unlike any form of transportation because it operates thousands of miles away from land and remains at sea for many days. This requires that the ship and its crew be a self-sufficient entity, able to deal with any number of possible accidents and emergencies.

Using automation reduces manning requirements but there is a point where the crew is just too small to remain alert and diligent, and able to safely operate the ship. Optimizing manning and designing effective human-machine environments is challenging but can be achieved through proper function allocation.

15.8.1 Function Allocation: The Challenge of Job Tasking

Function allocation can be defined as *the assigning of required functions to instruments, computer/automated systems, and human operators (24).*

It also can be looked at as the assignment of human operators or systems to required functions. Each interpretation results in a similar outcome and both are equally critical factors in the design of human-machine systems.

Assigning functions to available resources appears to be a very rational and logical process, but it is debatable.

There are a number of variables and considerations that must be taken into account when considering function allocation. Examples of such factors include economics, manpower, technology, morale, motivation, fatigue, and monotony. There are also issues in considering what resource is best assigned to a task. Humans and machines perform functions differently and with varying degrees of effectiveness. Paul Fitts, a world-renowned engineering psychologist from the 1950s, devised a list of some of these ideas:

Humans surpass machines in:

- detecting visual, auditory, or chemical energy,
- perceiving patterns of light or sound,
- improvising and using flexible procedures,
- storing information for long periods and recalling appropriate parts,
- reasoning inductively, and
- exercising judgment.

Machines surpass humans in:

- responding quickly to control signals,
- applying great force smoothly and precisely,
- storing information briefly and erasing information completely,
- reasoning deductively,
- performing repetitive and routine tasks, and
- handling high complex operations.

This list is controversial among experts who claim that it only compares the abilities of humans and machines and than decides which is best for each function. Despite this debate, there are a number of combinations of functions that can be assigned to both humans and computers. Many solutions have been theorized but considering the number of variables and unforeseeable occurrences, it is unlikely that this will ever become perfectly clear. However, many useful approaches and tools have been developed to optimize function allocation.

15.8.2 Successful Approaches in H-M Design

Two approaches can logically be taken to generalize the design process of human- machine systems, 1) adapt humans to technology, or 2) adapt technology to humans.

Perhaps neither of these is as good as the following proposal: *optimize the adaptation of both humans and machines simultaneously.* In other words, a successful human-machine design should give heavy consideration to both the human operator and the machine, and the designer should tailor the system so that both are able to operate efficiently and effectively.

Human-Machine systems should be designed so that both the operator and the machine perform at an optimal level. This can only be accomplished when both the human operator and the machine have been analyzed and their strengths and weaknesses are known. The human factors, such as fatigue, make it extremely difficult to come up with a foolproof design that can completely eliminate human error. Coupled with the fact that the environment in which these systems operate is extremely dynamic, and that both humans and machines can be very unpredictable, designing a successful human-machine system is a challenge.

Fortunately there are tools to help designers meet the challenge of constructing human-machine systems. The tools come in the form of system analysis and innovations in automation. Understanding how to use these tools can help designers optimize the systems and its outcomes.

The human operator should be perceived as an information processing system that gathers and interprets information to make decisions in any given situation. The decisions and actions taken by an operator can therefore be related to the quality and correctness of the information given. Bad decisions are typically the result of poor information; good decisions follow the same logic. Looking at it from this perspective means that designers must pay close attention to details such as information presentation, interface, and operator sensory perception.

Fatigue and other human factor variables require special attention in the design of complex human-machine systems. One of the main goals of this type of system design is best stated *as the prevention of skill breakdown under threats from unplanned and uncontrollable aspects of the work environment, such as stress states or extreme levels of demands* (25). One aspect of this approach has been to use automation to make life *easier.* The idea that automation enhances safety and decreases human error seems to be a reasonable assumption but this is can be debated.

15.8.3 The Use of Automation

The world relies heavily on automation to make things work. The use of automation has in some cases become necessary in order to perform complicated tasks or to operate complex machinery. A major problem with this is that automation doesn't always work. Blackman et al (26) cite the following technology failure related statistics from 1971 to 1991:

- 10 227 deaths/injuries from 150 airplane crashes,
- 6998 deaths/injuries from 22 ship disasters,
- 5353 deaths/injuries from 24 industrial explosions,
- 2046 deaths/injuries from railroad accidents, and
- 231 million gallons of oil spilled into the oceans.

These events were all the result of shortfalls and failure in technology. These statistics give rise to many questions about the use of automation in safety critical operations. There are two basic schools of thought on this:

1. pare down or limit the use of automation, and
2. pursue even greater advances in the use of automation (24)

This is another situation where finding a happy medium between the two may be the best answer.

Finding a workable level of automation in human-machine systems is not a simple task. The aviation industry has struggled with this problem for years. Advances in aviation have left designers with planes that cannot even fly without computer assistance. The airline industry also is faced with operating larger planes and covering longer distances. The use of automation in this type of environment is a necessity and it does not come without problems.

One particular automation debate concerns the use of automation in an aircraft that had the ability to automatically balance the fuel in the left and right wing tanks. The system was able to sense a difference in fuel levels without any input from the pilot and it could automatically transfer fuel in order to balance the weight. In theory this was an excellent idea because it decreased the number of tasks with which the pilots dealt. However, a leak in one tank caused the system to transfer all the fuel from the good tank to the leaking tank. The pilots were completely unaware as the automated system performed its function and the plane crashed. This situation provides an example of how quickly an innovation in fuel management automation can turn into a major catastrophe. It also provides a situation that can be analyzed in order to avoid such costly errors. Two ideas presented by Blackman et al (26) in the same automation debate were related to this problem, namely,

1. automation will reduce workloads, and
2. automation will reduce human error.

The two benefits that automation is believed to provide are two areas that also cause a number of problems for human operators. A reduction in workload is beneficial to the human operator in terms of task management but tends to pull the operator *out of the loop.* Using automation to monitor systems, such as in nuclear plant or industrial plants, eases the supervisory burden of such operators but can decrease the operators understanding of the systems status. In a high workload environment, operators can quickly lose control of a system if steps taken by automation are not readily displayed and understood. The automated system can quickly perform a number of tasks and this leaves the operator without a clear understanding of what happened in the transition or what is going to happen in the system. Using common risk assessment tools, such as a Fault Tree Analysis, and designing redundancy in the system are two approaches that need to be taken to combat automation reliability problems.

The use of automation to decrease human error also contributes to the loss of an operator's system status awareness. Computer controlled systems perform thousands of complex algorithms a second and their outcome may not always be apparent to the operator. The lack of understanding by the operator gives them a disadvantage in emergency situations. When emergencies do occur, the operator may have little or no idea about what has happened or where there was an error in the automation due to poor system control design. This lack of information and understanding quickly puts the operator in a dangerous and sometimes hopeless situation.

15.8.4 Automation-Too Much of a Good Thing?

Advanced automation often requires continual monitoring by human operators. Even the most advanced technologies can fail. Although their failure is a rare occurrence the consequences can be high.

Automation tends to lead to the use of unmanned systems, which can be inherently dangerous. Blackman et al (26) provide the following arguments why this type of automation is unacceptable:

- this type of automation is complex and therefore modes of failure are not always predictable,
- as automation gets smarter, human operators will have higher workload--especially sharper workload transients if failure occurs-and therefore have more difficulty taking over control, and
- for such systems, people will continually demand higher and higher performance and standards of safety.

Blackman et al (26) conclude by stating,

> insofar as human plus computer can do even marginally better than computer alone, people will continue to demand that a human be there.

It is his opinion that there is no choice but to deem automation by itself as inherently unacceptably safe for those circumstances where human life is at stake.

Hockey et al (25) carried out a study to test the compensatory control model, which predicts performance maintenance under stress at the expense of effort and increased selectivity. The study looked at the effects of sleep deprivation on performance in an automated process control task. The results of the experiment provide insight into the use of automation in maritime operations and just where fatigue comes into the picture. It seems that fatigued operators had better success when they had more control over the system and were able to take a preventative approach. When not able to do so, operators had less know ledge of plant status and could not react accordingly. Automation that can or must be continuously monitored and has the ability for operators to practice preventative maintenance gives operators a better chance of overcoming fatigue. This is not the current trend of using automation in the marine industry.

The current economics of maritime operations has led the maritime industry into taking a large interest in crew reduction and unmanned operations. There have also been a number of technological advances that have led to major changes in the role of human operators, many of which remove the operator from the systems control. Some of these advances have been listed and include automatic data logging, position fixing aids, restricted navigation aids, collision avoidance systems cargo planning aids, automatic route following, and maintenance diagnostic aids. **In** some cases these types of automation have reduced crew sizes from 30 to 40 crewmembers to 15 to 21 (27). Automation has turned many mariners into managers, responsible for coordinating and monitoring multiple automatic systems.

The use of automation on ships has had impacts on both the deck department as well as engineering. The advances made on the bridge have occurred in radar and progressed to radar enhanced with automated radar plotting aids (ARPA) and more recently electronic chart display information systems (ECDIS). Many countries are working on developing fully integrated bridges. The idea is to use multiple automated systems to produce a massive integration of navigation and ship control systems, possibly requiring the use of only one mariner on the bridge to acts as helmsman, lookout, and watch officer. Changes in the engine room have been no less dramatic (Figure 15.8).

The *old* system of engine room management mainly consisted of a wiper, a water tender, an oiler, a fireman, and an engineer. Modem ship design looks to use minimal personnel in the engineering spaces. As of late, automation has enabled many engine rooms to go unmanned. The machinery and spaces can be remotely monitored with engineers working there during the day and going "on call" during the night. This has definitely reduced costs in terms of manning but has greatly increased levels of stress among crew and especially captains. Lee and Sanquist (27) provide a comment from one ship's captain who said that having an unmanned engine room during voyages greatly increased his stress levels.

The problems associated with fatigue and automation have been discussed. Lee and Sanquist (27) have provided further examples of some of the problems associated with automation:

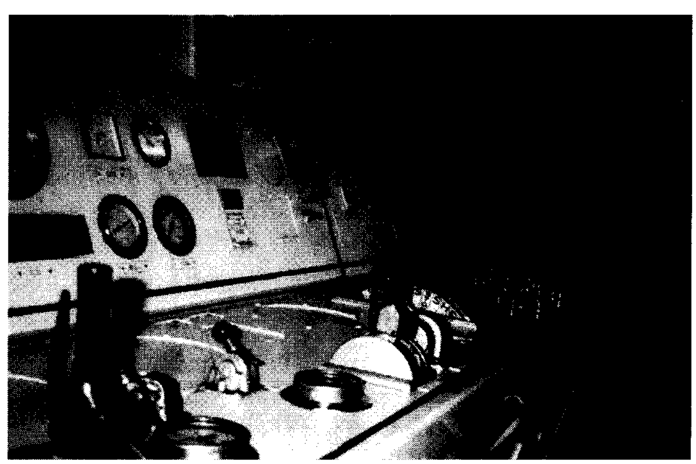


Figure 15.8 Typical Engine Room Control Panel

- skill degradation,
- inadequate feedback resulting in misunderstanding,
- miscalibration in trust of automation, leading to misuse,
- fewer physical demands but greater cognitive load,
- enhanced workload peaks and troughs
- inadequate and misleading displays, and
- reduced opportunity for learning.

Many of these examples are aggravated by fatigue. For example, fatigued operators with a low skill base will have less of an understanding in how to react in an emergency. Inadequate feedback does not enhance the ability of either a fatigued or refreshed operator. When fatigued, an operator can benefit from physical activity such as inspecting machinery and reading gauges. The use of automation has eliminated this and transferred the physical workload to the cognitive workload. This is especially a problem because decision-making and reasoning ability are greatly affected by fatigue. Lastly, the increase in workload peaks and troughs are not controllable and both are detrimental.

After looking at the information on human fatigue, human-machine interface, and automation, it is clear that these issues require further research. One thing for certain is that ship designers and operators will continue to be faced with innovations and advancing technology that mayor may not make maritime ship operation easier and safer. Being able to identify what types of automation and system interface are most useful are important skills that designer's must posses when looking at the future. The human-machine environment can be very unpredictable and dynamic and is even more so when designed to operate in the most unpredictable and dynamic system of them all, Mother Nature.

15.9 WHERE TO GO FROM HERE

Naval architects and marine engineers have the ability to positively affect the final product of marine design. This chapter will hopefully provide the reader with a good understanding of the importance of adequately addressing human factors in the ship design process.

It cannot be stressed enough that *designingfor* the human from the ground up is essential to effective system design and operation. This type of approach ensures that the human operators are able to perform their duties safely and effectively. The long-term benefits of increased health and well being promote safe operations and reduce costs. The current trend of attributing the blame for accidents and mishaps to the human is shifting to the very nature (design) of the system the human is required to operate. In other words, human error is more often than not the result of a poorly designed system and ill-managed operation, that is, an *accident waiting to happen.*

The authors therefore hope that this information ~ill provide the naval architect and marine engineer with a new outlook and different perspective regarding the design process. The marine environment is like no other, and the demands placed upon humans necessitate their full consideration within the design process. Through this effort, a more habitable environment can be attained, and one that serves to optimize the skills and abilities of the people operating the system.

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Chapter 16

Safety

Robert L. Markle

16.1 PREVENTION

Safety is a key element to the design, construction and operation of any ship or vessel. No one wants to design or construct an unsafe vessel, but the key to prevent doing that is to design in safety features that will prevent accidents and injuries that can occur during construction or operation. While this book is about designing and constructing ships, the use to which these structures will be put cannot be ignored. The most important safety consideration on any ship is the prevention of accidents. Over the years accidents have been investigated to discover why the particular incident occurred, and to prevent that particular type of event from reoccurring. Accident investigators look at the chain of events leading up to an accident, and the events, which occur after it. Designers try to develop engineering solutions to safety problems that are found. Often engineering solutions try to break the chain immediately before the accident occurs, or shortly afterward in order to mitigate the effects ofthe accident (Figure 16.1). Preventing accidents requires that the chain be broken at the beginning, by getting at the root cause-the error that led to the accident in the first place. That error might be an organizational error, perhaps the way the organization trains or assigns its personnel. It might be due to fatigue or physical impairment either as a result of an organizational error or a lifestyle choice made by an individual. It might be a design-induced error; perhaps a poorly designed control station. Therefore, prevention involves not only the technological side of ship safety, but also the people and the organization involved in operation of the ship.

A broader view of prevention is needed, a view, which takes into account what might occur rather than simply what has occurred.

To do this, the human element, the people who will be using the vessel must be taken into account. Without taking the human element into account, we create systems that will be more likely to cause an accident or injury. The other key element to remember is the people who will be working on and with these vessels. Prevention is the key, because it is easier and cheaper to prevent accidents rather than trying to minimize the consequences of an accident.

Designers affect how the ship is constructed, and whether the workers in the shipyard will have a hard time building it. They affect the price too, because if a ship is more difficult to build, the yard will spend more man hours and thus need to charge more. In addition, if a section of the ship is too hard to build, short cuts may be taken that can weaken the structure. Designers also affect the operation and maintenance of the vessel. If machinery is shoehorned into a difficult to reach place, then maintenance and repairs may not be properly completed. It also makes the ship difficult to inspect to ensure its safety. The design also can affect the costs and ease of decommissioning a vessel or structure.

Consider the problems that exist today with scrapping an old ship built with asbestos throughout. Admiral J. C. Card, in his unpublished address to Webb Institute of Naval Architecture in March 25,1997, *Keep accidents from happening-build a safer ship,* stated that:

> too often this problem is solved by scrapping the ship in a country where a low priority is placed on safety.

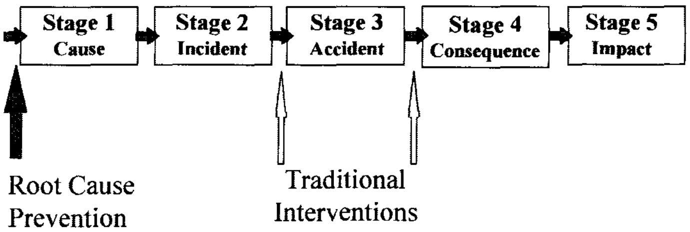

Figure 16.1 Chain of Events of an Accident

16.2 THE HUMAN FACTOR

What can a ship designer do to take the human factor into account? It is important to remember that people are involved throughout the life ofthe ship, from design, through construction, operation, modification, and scrapping. Crews cannot be expected to compensate for poor design or inadequate technical documentation for the life of the ship. Design teams should include human factors engineers, or at least engineers who have been well trained in human factors principles (see Chapter 15 - Human Factors in Ship Design).

Many studies have shown that, statistically, the engine room is the most dangerous area on a vessel. It's also one of the most critical components of effective accident response with controls for pumps, power and propulsion. Therefore, it stands to reason that a well-designed engine room will be more inherently safe and will contribute to the overall safety of the vessel. The International Maritime Organization (IMO) has developed guidelines for engine room design, layout and arrangements (1). The purpose of these guidelines is to provide to vessel designers, owners, operators and crewmembers information to enhance engine room safety through design, layout, and arrangements. The relevant factors that the guidelines address are:

- familiarity (the standardization of engine rooms so that crewmembers new to a ship can become proficient in its operation quickly),
- occupational health,
- ergonomIcs,
- minimizing risk through layout and design, and
- survivability (which addresses that crew's capability to survive and counteract an engine room emergency).

But, the engine room is not the only place on a ship which requires attention to good human factors design. People interact with the ship system from bow to stern. The American Society for Testing and Materials (ASTM), has developed a human factors design standard based on military standards and research, ASTM F 1166-88, Standard Practice for Human Engineering Design for Marine Systems, Equipment, and Facilities, which provides guidelines for designing the person into the system. What kinds of considerations go into good human factors design?

Here are a few examples:

- During a human factors survey of a ship under construction, one of the items noted was that the "trick wheel" for the emergency steering gear faced the starboard bulkhead. Ideally, controls should operate in a "logical" direction, which in this case would have required relocation of the wheel. But, this installation did not even include any signs or markings to indicate which way the rudder would turn when the wheel was moved. This would be vital knowledge in the event of an emergency.
- Writing on signs should be large enough to read quickly in an emergency. Colors and symbols used should be consistent with accepted standards.
- There should be sufficient clearance in a passageway for someone to walk along without hitting his or her head on an overhead pipe.

16.2.1 Error-tolerant Design

In spite of flawless system design, and extensive crew training and readiness, people will occasionally make mistakes. These errors arise from:

Lapses-Forgetting or confusing the proper procedure.

Slips-Physical errors where a proper action was intended.

Mistakes-Mental errors.

Violations-A willful circumvention of the proper procedure.

Ship systems should be designed so that errors or equipment failures are evident when they occur, and that a single problem does not lead to a series of additional errors or a catastrophic result. In 1995, the cruise ship *Royal Majesty* ran aground off of Nantucket 10 miles from shore and 19 miles off its intended track. The National Transportation Safety Board traced the cause of the grounding back to an antenna failure for the Global Positioning System (GPS). The GPS signal fed into the integrated bridge system, which steered the ship along a preprograrnmed track line. The GPS defaulted to dead reckoning (DR) when it lost the satellite signal, and sent that DR position on to the integrated bridge system. For its part, the integrated bridge system ran its own DR to check the position input, unfortunately using the same speed log and gyro input as the GPS used. The result was two computers running DRs using the same data and, as a result, tracking perfectly. Unfortunately, set and drift were not accounted for, the radar was on a three-mile range, and the officer on watch did not recognize that the lights visible on Nantucket shouldn't have been. Further, the GPS failure alarm was a *beep beep* like you might hear from your wristwatch, the DR mode indicator was an obscure light on the operation panel, and the system was located back in the chart room. This was a good ship, operated by a good company, and manned by good officers, yet overreliance on technology and a lack of understanding of what went on inside those black boxes led to complacency and the endangerment of hundreds of passengers.

A systematic human factors approach requires evaluating the standards for implementing new technology, including using risk tools such as a failure modes and effects analysis, considering the work environment of the mariner so that critical signals are received and understood, reviewing the activities, training and motivation of the mariner, and examining the management of the vessel to ensure that complacency does not allow accidents to occur.

16.2.2 Construction and Equipment

The culture within the marine industry is changing toward one that incorporates safety as a primary consideration in the routine performance of business-a safety culture. This is embodied in IMO's International Safety Management Code, which is now mandatory for ships on international voyages. The same considerations need to govern the design and construction of ships.

Sometimes, however, even the best designed ship manned by a highly competent crew will be involved in a casualty that will require surviving a fire, or if everything else fails, abandoning the ship. The remainder of this chapter discusses lifesaving measures to deal with fire, and ship abandonment.

16.3 FIRE SAFETY CONSTRUCTION

Fire at sea can be especially difficult to control and extinguish because there is no dedicated professional fire department, and the problem is complicated by the complex structure of modem large merchant vessels. Therefore, it is important to make sure that incipient fires are contained at their origin. Specifically, the structure should not add to the fire severity and the structure should contain the fire to the room of origin. This is most easily accomplished by using noncombustible materials for the ship's structure. In addition, the use of materials, which do not readily ignite or are proven to resist the spread of flame, should be used in the outfitting and furnishing of the vessel.

16.3.1 Conventional Construction

Both the U.S. and international regulations for cargo vessels, tankers, and large passenger vessels require the hull, superstructure, and structural components to be constructed of steel or equivalent material. One of the basic premises of this requirement is that the material be noncombustible as defined by a very stringent marine-specific test procedure. This includes materials used in the hull, superstructure, bulkheads, decks, ceilings, linings, stairs, doors, and windows.

Another important premise is that the material shall not be heat-sensitive or else shall be insulated to maintain a predetermined core temperature criterion. *Heat-sensitive* is determined by exposure of a material to a representative fire test, which produces the same time-temperature curve used in the shore side building industry. For a one-hour exposure, the material will be exposed to temperatures in excess of 900°C. Materials like aluminum, although not combustible, will melt during the fire exposure, and thus are heat-sensitive and must be insulated to perform in a manner similar to steel.

Other materials used for furnishings, finishes, or decorations may be combustible but have significant limitations. These limitations may include total volume, total mass, thickness, calorific value, or flame spread or flammability characteristics. The requirements vary by ship type, ship service, or individual compartment designation. For example, the international regulations place restrictions on surface flammability of all interior finishes of accommodation, service, and control spaces of passenger vessels while U.S. regulations only make such restrictions on corridors, stair towers, and certain *low risk* accommodation spaces.

In general, the insulation requirements for decks and bulkheads are related to the expected hazard based on the compartment use. For example, the integrity of a bulkhead may require resistance to the passage of flame and smoke for one hour if the compartment is used for machinery or stowage of cargo. On the other hand, a compartment, which uses fire-resistant furnishings and maintains a reduced total amount of combustibles, might only require a barrier rating of thirty minutes. The above examples are an oversimplification, and the factors, which affect the barrier requirements, are substantially complex. Engineers who are responsible for ensuring compliance with either the U.S or international regulations must be very familiar with all of the requirements.

Besides barrier integrity and material properties, other structural fire protection requirements include fire door integrity, ventilation damper integrity, cable penetration fire stops, window fire integrity, and structural insulation to prevent heat transfer through the steel divisions. All of these items would degrade the integrity of divisions if not properly constructed.

If the ship's structure is noncombustible, barrier integrity is maintained, and materials used in outfitting the vessel are resistant to ignition and flame propagation, then the ship's structure from a fire safety standpoint will be effective in reducing loss to life and property.

16.3.2 Advanced Materials

Although there is a host of *advanced materials available* for marine construction, the majority of these materials are not practical for commercial applications simply because they are not competitive with steel or aluminum. The most affordable and therefore the most promising materials are fiber-reinforced plastics (FRP) (see Chapter 21 - Composites). As the name implies, FRP consists of resins, reinforcement fibers, and sometimes core materials. Some of the typical FRP materials that may be utilized in marine construction are listed in Table 16.1. (1,2). These materials can be used in various combinations and formulations depending on the specific application.

The current U.S. and international regulations require ship construction materials to be non-combustible. This restriction has prohibited the marine industry from fully exploiting the advantages of FRP in vessel construction. The bulk of these regulations were developed before FRP was considered as a primary material for ship construction and they need to be re-examined in light of the state of the art. A brief discussion of the history of the development of regulations, an overview of existing regulations, and a discussion of the future of FRP materials is provided below.

16.3.2.1 History

The current international and domestic requirements for structural fire protection on vessels have a long history dating back to the Second International Convention for the Safety of Life at Sea (SOLAS) in 1929 which required construction with *fire-resisting bulkheads.* In 1934, the passenger ship *Moro Castle* burned off the coast of New Jersey resulting in the deaths of 124 persons (Figure 16.2).

Public outcry from the incident led to the creation of a special subcommittee by the Senate and subsequent U.S. ratification in 1936, of the 1929 SOLAS Convention. The subcommittee included a Fireproofing and Fire Prevention group set up to consider measures to avoid the rapid spread of fire up and down stairways, along corridors, and through accommodation spaces that occurred on the *Morro Castle.* They determined that the best method of controlling fire spread *would be construction of such nature that it would confine any fire to the enclosure in which it originated.* This view has become one of the fundamental principles of structural fire protection reflected in both U.S. and international regulations today. It is important to note that the subcommittee's philosophy relied on the nature of construction.

TABLE 16.l FRP Construction Materials

Resins	*Fiber Types*	*Core Materials*
Polyester	E-glass	End Grain Balsa
Vinyl Ester	S-Glass	Linear PVC
Epoxy	Aramid	Cross-Linked PVC
Phenolic	Carbon	Nomex
Polyamide	Ceramic	Ceramic
Bismaleimide	Metallic	Aluminum
Thermoplastic	Thermoplastic	None

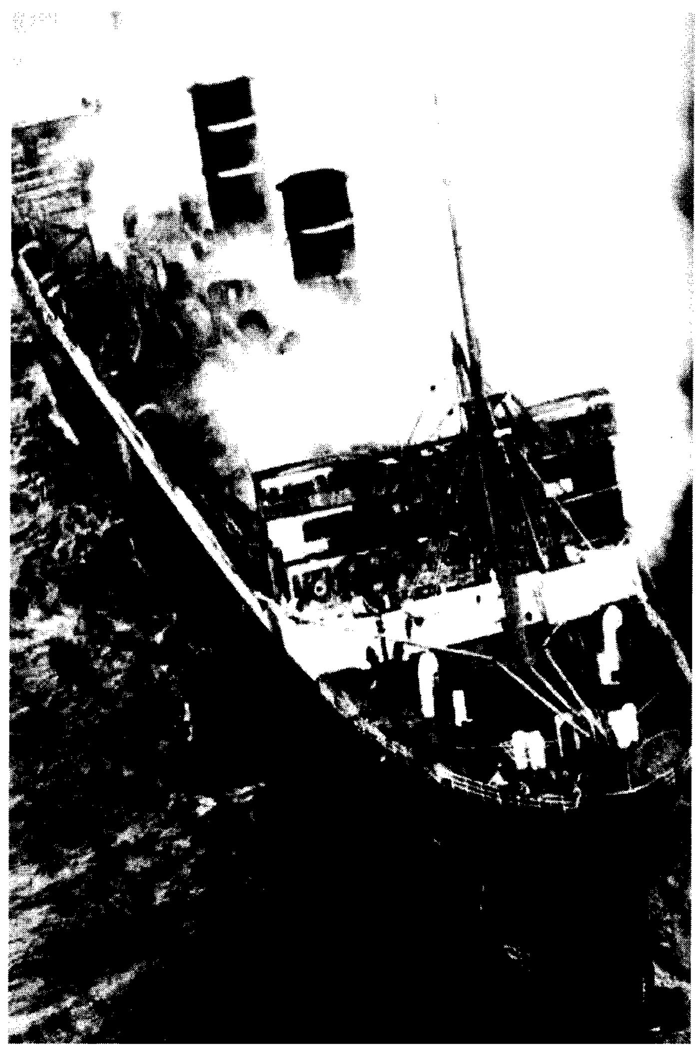

Figure 16.2 *Morro Castle*

This means that in confining the fire to the space in which it originated, reliance on any automatic or manual systems of control was eliminated, and the structure itself could be relied on to contain the fire. The subcommittee's view was that this philosophy, which is known today as *passive* fire protection, was the most foolproof means of confining a fire.

Starting in 1936, a series of fire tests were conducted on board the test ship SS *Nantasket* that resulted in the development of a form of construction in which combustible material was eliminated to such an extent that combustion could not be sustained by any part of the ship's structure. In April of 1948, many of the findings from the SS *Nantasket* testing were incorporated into international regulations at the third SOLAS Convention. The 1948 Convention was followed by two later conventions, SOLAS 1960 and SOLAS 1974, which added further improvements to international structural fire protection requirements.

Today, the structural fire protection philosophy is based on many full-scale tests and experiences and can be summarized by the following SOLAS principles:

- division of ship into main vertical zones by thermal and structural boundaries,
- separation of accommodation spaces from the remainder of the ship by thermal and structural boundaries,
- restricted use of combustible materials,
- containment and extinction of any fire in the space of origin,
- protected means of escape and access for fire fighting,
- readily available fire extinguishing appliances,
- minimized possibility of flammable cargo vapor ignition, and
- detection of any fire in the zone of origin.

These principles are reflected in the prescriptive requirements of the U.S. Code of Federal Regulations (CFR), the international SOLAS Convention, and the Code for the Construction of High Speed Craft (HSC Code). The prescriptive requirements (with the exception of the HSC Code) that address the first five principles listed above were developed before the advent of advanced composite materials. For the most part, these five principles are met through prescriptive codes requiring passive fire protection construction.

16.3.2.2 U.S. regulations (3)

Following the passive fire protection philosophy discussed previously, the U.S. regulations generally require the hull, structural bulkheads, decks, and deckhouses to be constructed of steel unless an arrangement of other materials can be shown to perform equivalent to steel. This is illustrated in Table 16.II, which contains excerpts from the Code of Federal Regulations (CFR). It is clearly the intent of the regulations that ships be constructed from materials that are non-combustible and tolerant of high temperatures.

Historically, the U.S. Coast Guard defined *steel equivalence* as being a metallic or non-combustible material having a melting point not less than 925°C. This definition is a major obstacle to the increased use of advanced composite vessel construction. As demonstrated in the table, the regulations are somewhat more lenient for small passenger vessels carrying 150 passengers or less.

These vessels may be constructed of fiber reinforced plastic provided the material system is shown to be fire retardant when tested to military specification MIL-R-21607 or if it is found to have a flame spread rating of 100 or less as measured inASTM E-84, Surface Burning Characteristics of Build-

TABLE 16.II U.S. National Structural Fire Protection Regulations

Vessel Type	*Regulation Cite*	*Construction Requirement*
Tank Vessel	46 CFR 32.57-10	Steel or other suitable material having in mind the risk of fire
Large Passenger Vessel	46 CFR 72.05-10	Steel or other equivalent metal
Cargo Vessel	46 CFR 92.07-10(a)	Steel or other suitable material having in mind the risk of fire
Mobile Offshore Drilling Unit	46 CFR 108.133	Steel or equivalent material
Small Passenger Vessel >150 Passengers	46 CFR 116.415(a)(1)	Steel or equivalent material
Small Passenger Vessel <150 Passengers	46 CFR 167.10-5(a)	Minimize fire hazards insofar as reasonable and practicable
Oceanographic	46 CFR 190.07-10(a)	Steel or other suitable material having in mind the risk of fire

ing Materials test. These vessels are also permitted to be constructed of composite materials that do not meet the above tests provided the vessel meets several other requirements, including a fixed extinguishing system in the engine room.

16.3.2.3 International regulations 141

The international requirements governing the use of materials in ship construction are primarily defined in the International Convention for the Safety of Life at Sea (SaLAS). This international treaty has, in the past, permitted construction with combustible materials if an automatic sprinkler system was installed (known as method III). In 1994, however, due to casualty history, the SaLAS requirements for passenger vessels were amended to require construction with approved non-combustible materials and automatic sprinkler systems. Recognizing the need for lightweight, high-speed ferry type craft (Figure 16.3), the international community developed the International Code for the Construction of High Speed Craft (HSC Code). The HSC Code allows the use of combustible construction but only when the materials meet very strict definitions (discussed in Section 16.3.2.5) for *fire-restricting materials.*

The Test required for materials to be classified as *fire-restricting* are very difficult for composites to meet. Currently, there are no structural composite material systems that can meet the requirements and still competitively compete with aluminum construction.

This leniency is allowed because the HSC Code requires the vessels to meet very strict operating, management and evacuation requirements.

Some non-structural composites have successfully met the fire-restricting material requirements in the HSC Code. Table 16.III identifies the applicable International Requirements.

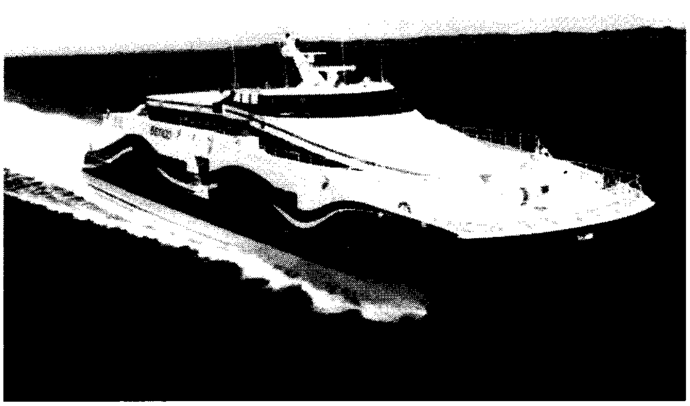

Figure 16.3 High Speed Craft

16.3.2.4 Future direction

As demonstrated previously, the international and domestic regulations essentially require steel construction unless some other system can be shown to perform in an equivalent manner. Traditionally, equivalence to steel has been interpreted as meaning a non-combustible material, which by itself or due to insulation provided has structural and integrity properties equivalent to steel. These regulations were developed in light of the technology available at the time. Today, the development of advanced composite materials promising high performance and reduced maintenance, demands that regulations developed in the past prohibiting these new materials, be examined and altered in light of current technology. Indeed, the world community appears ready and willing to accommodate new materials provided that a thorough and technically sound analysis is completed that ensures the current level of safety is maintained.

Excerpts from the preamble of the HSC Code are evidence of this in stating:

> The traditional method of regulating ships should not be accepted as being the only possible way of providing an appropriate level of safety, nor should it be assumed that another approach, using different criteria, could not be applied.
>
> Management of risk through accommodation, arrangement, active safety systems, restricted operations, quality management and human factors engineering should be considered in evaluating safety equivalent to current conventions. Application of mathematical analysis should be encouraged to assess risk and determine the validity of safety measures.

16.3.2.5 Advanced materials construction and the HSC code

To date, no vessels have been constructed with a substantial amount of composite materials that meet the HSC code. The main reason for this is the requirement that combustible materials be fire restricting. This requires that they meet strict criteria in the ISO 9705 standard (room corner test). Currently, composite materials typically used in the construction of marine vessels cannot meet the requirements (heat release and smoke production being the disqualifying factors) without some form of insulating media. The addition of insulation to the hull, superstructure, structural bulkheads, decks and deck-houses, results in weight and cost penalties that eliminate composites when competing with aluminum construction. Aluminum vessels only require insulation in areas classified as fire-resisting divisions; composite (combustible) constructed vessels not only require insulation in these areas, but also everywhere else, in order

TABLE 16.III International Structural Fire Protection Regulations

Vessel Type	*Regulation Cite*	*Construction Requirement*
Tank, Cargo, or Passenger Vessel	SOLAS, Chapter II-2, Regulations 3.2.1, 3.43, 9, 11.2, 18.3.1	Steel or equivalent material
High Speed Craft	HSC Code, 7.4.1.3	Non-combustible or fire restricting materials

to qualify as fire-restricting. This is the Achilles' heel of composites use on HSC Code compliant vessels.

16.3.2.6 Advanced materials construction and SOLAS vessels

The use of composite materials for the construction of SOLAS vessels is made difficult by the SOLAS requirement that materials of construction be non-combustible. The first step towards allowing the use of advanced materials construction of these types of vessels is by beginning with vessel structural components. Numerous components have been identified that could be used for SOLAS vessels. For example, cargo hatches, vehicle ramps, deckhouses, helicopter decks, platforms, rudders, masts, etc. Although SOLAS does not allow combustible construction, the precedent has already been set for the use of combustible components. Regulation 16 of Chapter II-2 allows the use of combustible ventilation ducting in certain areas.

16.3.2.7 Fire concerns

As demonstrated previously, much of the current body of regulation was developed prior to the advent of advanced composite materials. The maritime regulatory bodies are exercising extreme caution with regard to the use of advanced materials because their fire performance is not yet completely understood. One summation that succinctly captured the fire concerns of the maritime industry stated that:

> fire, in particular provides no end of hang-ups, as everyone who has thrown a plastic bag on the fire is utterly convinced that composites offer no fire protection whatever. They are shown a film of the lower part of the shuttle glowing red, then white as it re-enters the earth's atmosphere. They are told of demonstrations where a composite tank of water heated in a 2000°C fire for two hours with the temperature rising less than one degree and the tank unaffected by the inferno. There are fire tests where composite fittings on aluminum survive unscathed where the surrounding structure vanishes entirely. Just as advocates of wood construction in the 1800's spoke of the dire consequences of building ships of iron, advocates of steel today speak the same way of composites (5).

In order to overcome the fears and further the use of advanced composite materials aboard ships, the fire performance issues must be addressed through rigorous technical analysis and design. The results of these types of analyses will encourage the safe and effective use of these materials in marine construction. There is much work currently being performed in both the United States and other countries by both private and government constituents and agencies. As a result of these research activities, the use of composites will be significantly expanded in marine vessel construction in the near future. As the verse below suggests, once the fire safety issues are adequately addressed, the advantages of marine composites including low initial cost, weight, corrosion resistance, long-term life cycle costs, etc., will significantly expand the use of these materials in marine construction.

Of rust you will not see a bit
For everything is plastic
And if by chance a rock is hit
We bounce off like elastic (5)

16.4 FIREFIGHTING SYSTEMS

In spite of careful attention to fire safety construction, fires still occur on ships, and ships have to be equipped to fight them. Different types of fire fighting systems are used, depending upon the space and hazard to be protected.

16.4.1 Fire Mains, Hydrants, Hoses and Nozzles

Water for fighting fires throughout the ship is supplied through the fire main. The fire main provides water to the hydrants each of which is equipped with a length of fire hose and a fire hose nozzle. The hydrant, hose and nozzles must have the same thread throughout the ship to be interchangeable, usually National Standard thread.

16.4.1.1 Hydrants

Hydrants consist of a control valve, a hose connection, and a hose rack (Figure 16.4).

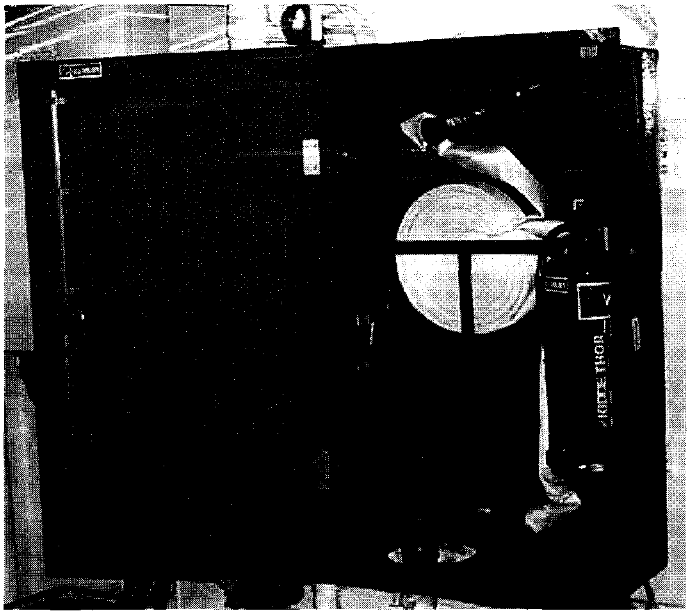

Figure 16.4 Hydrant with Hose and Nozzle

Hydrants must be sufficient in number and so arranged that two effective streams of water can be directed into all portions of the vessel accessible to passengers and crew. One of the streams must be from a single length of hose. The hose must be long enough to direct water into all portions of the space and not just long enough to get the nozzles to the door. Except for hose on the weather deck of tankers, all hose of the same diameter should be of the same length, to assure that hose of the proper length will be returned to each hydrant after being removed for testing or cleaning. Hydrants are tested to determine that they meet minimum pressure requirements by using smooth bore nozzles, not combination or adjustable fire hose nozzles.

16.4.1.2 Hose

U.S. regulations require fire hose either ofthe 38 mm or 64 mm size of 15 m length, and must be connected to the hydrant at all times. The larger diameter hose is used on larger vessels. However, since it is difficult to handle the larger size hose particularly in interior spaces, for interior locations, the 64 mm hose may be replaced by a Siamese connection to 38 mm hose. One hose of 38 mm diameter of not more than 16.5 m is sufficient. When the hose may be damaged by heavy weather or when it interferes with the handling of cargo, it may be temporarily removed from the hydrant and stowed in an accessible location nearby. The hose must be rubber-lined fire hose labeled *UL* 19, as typically used by municipal and industrial fire departments. Another common fire hose, labeled *UL* 219, is not acceptable since it is intended only for use by occupants of buildings and is not intended for the wear and tear of regular duty by fire department personnel and vessel crews.

16.4.1.3 Nozzles

The traditional U.S. Coast Guard combination fire hose nozzles have three positions: straight stream, fog, and off. The fog outlet is intended to be fitted with a bent applicator whose function is to provide a fine fog for protection of fire fighting teams and for being able to reach around comers. Based on a determination that their performance was equivalent to that of the traditional nozzles, the Coast Guard has approved certain adjustable nozzles, which neither need nor incorporate applicators. While the traditional nozzles may continue to be used, Coast Guard regulations were recently revised to permit the approval of adjustable nozzles, which comply with ASTM F1546.

16.4.2 Sprinkler Systems

Sprinkler systems consist of a water supply, piping network and spray nozzles intended to deliver water to an area for the purposes of fire suppression. Shipboard sprinkler systems can be divided into two categories: *automatic* and *manual.* Automatic sprinkler systems usually consist of thermally actuated spray nozzles and a piping network, which is continuously charged with water. Automatic systems have the advantage of providing water at the exact location of a fire without the need for human action.

Open spray nozzles are used in manual sprinkler systems, which are intended to provide water to large areas such as open vehicle decks for the purposes of preventing fire spread and minimizing heat transfer from burning objects.

16.4.2.1 Automatic systems

Historically, automatic sprinkler systems have not been used on U.S. registered vessels; however, they were used on SOLAS vessels which were constructed in accordance with *Method II* (Method II allows the use of combustible construction in conjunction with automatic sprinklers, and is no longer permitted on SOLAS passenger ships, but it is still permitted on SOLAS cargo vessels other than tank vessels.) However, recent changes to domestic and international regulations have brought about an increase in sprinkler installations. Small passenger vessels, which carry more than 150 passengers and which are fitted with either an atrium or a balcony with an opening area less than 93 m^2 must be fitted with a sprinkler system. Also, the 1992 amendments to SOLAS require automatic sprinkler systems on all new passenger ships and all existing passenger ships by either 1997 or 2005 (or 15 years after the vessel's build date, whichever is later) depending on whether or not the vessel complies with SOLAS 74 as applicable to ships built on or after May 25, 1980.

Automatic sprinklers are essentially heat detectors, which operate after being heated to their activation temperature. This results in a very efficient water delivery since water is only delivered where it is needed. Typically, water discharge from automatic sprinklers is less than water discharge from fire main systems due to the relative speed of operation of sprinkler systems when compared to manual application of water from fire main systems. Since an automatic sprinkler operates more quickly than water can be manually applied, the fire is at an earlier stage of development, which requires less water for suppression. However, this advantage disappears when systems are designed to require human intervention to initiate water flow, such as by installing normally closed valves.

There are four types of automatic sprinkler systems:

1. wet pipe,
2. dry pipe,
3. preaction, and
4. deluge.

Wet pipe systems, which are most commonly used on ships, employ a pressurized water tank to maintain a pressure head in the piping and to provide an initial water supply. After operation of sprinkler(s), a sensor detects the loss of pressure in the water tank and starts a pump, which takes suction from the sea.

In dry pipe systems, which are typically used in areas, which may be subjected to freezing temperatures such as exterior areas, piping is filled with pressurized air. A dry pipe valve holds back a pressurized water supply until operation of sprinkler(s) allows the pressurized air to bleed off. For small interior areas, which are subject to freezing temperatures, such as cold storage rooms, wet pipe systems may be used with dry pendant sprinkler heads. Dry pendant sprinkler heads employ a nipple with a seal at the end of the connection to the water supply, which is held in place by a rod connected to the sprinkler's fusible element. Operation of the sprinkler causes the rod to release pressure on the seal and water to enter the nipple and discharge through the sprinkler.

Preaction systems are used in areas where there is a particular concern about accidental discharge of water. Preaction systems are similar to dry pipe systems, except that water is only introduced into the piping after operation of a supplemental detection system. However, since the probability of accidental operation of sprinklers is extremely remote, and proper installation and pressure testing of piping can eliminate leaks, the added cost of a preaction system is typically not necessary.

Deluge systems are rarely found on ships. They use open sprinklers and a valve, which is kept closed until it is opened. by a supplemental detection system. This valve is identical to the type used in a preaction system.

Design of automatic sprinkler systems is beyond the scope of this chapter. However, there are several good references on the subject (6,7). Like any engineering system design, the design of automatic sprinkler systems can be complex and should be performed by experienced processionals.

16.4.2.2 Manual systems

Like deluge systems, manual systems employ open sprinkler heads. However, the flow of water is initiated manually. Large areas may be divided into smaller zones to limit water supply requirements. Also, manual sprinkler systems typically do not use the pressurized water tank used in automatic systems. Activation of the system operates a pump(s), which serves as the sole water supply.

The primary application of manual sprinkler systems is vehicle decks of ferry vessels. The system is intended to achieve three goals:

1. complement the vessel's structural fire protection system by cooling space boundaries,
2. confine a fire to the location of origin, usually the vehicle of origin, and
3. wash flammable liquids to a safe location.

16.4.3 Gaseous Extinguishing Systems

Gaseous fire extinguishing systems are evolving rapidly. The original gaseous extinguishing media, carbon dioxide ($C0_2$), is still sometime used in machinery space fire protection. CO_2 needs to be stored in its liquid phase in order to reduce volume to a minimum, so that either low temperature or high-pressure storage is needed. High-pressure CO_2 systems use banks of cylinders to store CO_2 at pressures around 14 to 21 MPa. Low-pressure systems store CO_2 at low temperatures, so a refrigeration system is needed in addition to a large pressure vessel.

For many years, Halon was seen as the ideal gaseous extinguishing agent. It was effective as an extinguishing agent, clean, reasonably affordable, and low enough in toxicity that it would put out fires in spaces without presenting an immediate danger to persons in those spaces. Halon is a halogenated hydrocarbon implicated in the depletion of the ozone layer. The Montreal Protocol ended production of halons in industrialized countries in 1995. Even though halon banking and recycling of existing halon stocks is permitted under the Protocol, IMO has taken the additional step of prohibiting new halon system installations, thus hastening the search for replacement clean agent extinguishing systems.

For a while, it appeared that CO_2 systems would enjoy new popularity, and to some extent, that has been the case. However, CO_2 is a *greenhouse gas* and therefore has its own environmental drawbacks. Furthermore, it is toxic, as has been tragically illustrated with deaths occurring during accidental CO_2 extinguishing system discharges.

There are now numerous halon replacement extinguishing agents available, and they are starting to be installed on ships in place of halon systems. None of them are quite as effective as halon, and all are somewhat more toxic, and more expensive. That means that larger volumes of gas are required to extinguish comparable fires, but care must be given not to use too much in manned spaces. In any case, personnel working in spaces protected by gaseous extinguishing agents must recognize both intentional and unintentional discharges, and the need to evacuate areas in which discharges occur.

16.4.4 Water Mist Systems

Another extinguishing method gaining in popularity is water mist. These systems use high-pressure water delivered through nozzles that create a fine mist to extinguish the fire. These systems can be effective in extinguishing machinery space fires, and can also replace standard sprinkler systems. They can be an attractive way to retrofit sprinkler systems in existing ships because smaller piping can be used, as compared with conventional sprinkler systems. Therefore, water mist may be the system of choice for many passenger ships faced with sprinkler retrofit requirements under the SaLAS Retroactive Fire Safety Amendments.

16.4.5 Foam Systems

Foam is an effective means of extinguishing and, for a period of time, protecting flammable liquids in depth against re-ignition in areas open to the atmosphere. Other agents may extinguish fires in flammable liquids, but generally lack the ability to prevent re-ignition of flammable liquids in unconfined areas. That is why tank vessels are required to carry fixed foam fire fighting systems to protect their cargo decks. These foam systems protect the tanker's cargo deck through a series of fire fighting stations spaced generally along the centerline of the ship on the cargo deck, where they can be quickly placed into operation. Each station contains one fixed foam monitor and at least one hose with a portable foam nozzle. The system relies on the monitors to provide the bulk of the foam (a minimum of 50%). The hoses are used to supplement the monitors and apply foam in areas, which are difficult to reach with the monitor, such as in close proximity to the fire fighting stations.

The design application rate, that is, the amount of foam per tanker deck area or cargo tank area is prescribed by regulation, and exceeds the fire test application rate by a safety factor. The design application rate takes into account the size of the entire deck cargo area, the size of the largest cargo tank, and the size of the largest area protected by a monitor. The foam system must be able to apply foam for at least 20 minutes if the ship also has an inert gas system for the cargo tanks, 30 minutes if no inert gas system is installed. If the fire is not controlled within this period of time it is generally considered to be not controllable by the ship's crew.

The single most important component of the system is the foam itself. It extinguishes fires by forming a continuous blanket over the burning liquid, separating the combustible vapors from the oxygen necessary for combustion. Since foam contains water dispersed in a very thin film, it also has some cooling ability.

Mechanical foam is produced by introducing a specific amount of foam concentrate (either 3% or 6%) into a flowing stream of water through a foam proportioning system. The resulting foam solution is expanded mechanically through the mixing with air at the nozzle into foam, which is then discharged onto the tanker deck through fixed monitors and hand nozzles.

The effectiveness of the foam concentrate is established through fire and burnback tests intended to demonstrate the following:

- fire extinguishing effectiveness,
- ability to prevent re-ignition of flammable liquids for a period of time, and
- ability to resist foam breakdown and provide a seal against hot metal.

Foam concentrates are formulated individually by their manufacturers to be effective on certain groups of flammable liquids, and are not interchangeable without verification of their compatibility. Regular foams such as protein or fluoroproteins are formulated to be effective on hydrocarbon type flammable liquids such as crude oil, diesel, gasoline, aviation fuel, etc. Tankers carrying alcohols and other chemicals generally referred to as polar solvents, have a different problem since these chemicals break down regular foams, and such ships must therefore be equipped with foams specially formulated to be effective on polar solvents. Some chemicals break down foams so rapidly that even polar solvent foams must sometimes be discharged at a higher rate than foams protecting only hydrocarbon cargoes.

The need to be able to carry both hydrocarbons and polar solvents on the same ship has resulted in the development of foam concentrates, which are effective on both regular and polar solvent cargoes. Most recent marine foams are aqueous film forming foams formulated to be effective on both, but sometimes a higher concentration and significantly higher application rate is required for polar solvents.

Foam concentrates have limited shelf lives, and must be evaluated periodically for their continued usefulness. This is accomplished by sending concentrate samples to the system manufacturer for certification that the concentrate is still suitable for fighting fires.

Current problems result from the fact that significant amounts of chemicals (additives) are being added to gasoline, sometimes stretching the ability of the regular foam system originally designed for hydrocarbon cargoes to adequately protect the new gasoline/additive blends. Fires involving the latter are typically more difficult to extinguish than gasoline fires alone.

16.5 ESCAPE

In the event that shipboard emergencies cannot be controlled, evacuation becomes necessary. Shipboard evacuation consists of several steps:

1. notification of evacuation,
2. movement of people through egress routes,
3. mustering of passengers while the crew attempts to end the emergency or prepare survival craft, and finally
4. boarding of survival craft.

Not all of these steps will occur in each emergency. For example, vessel crew may successfully take corrective action while passengers are mustered on a passenger vessel.

The basic tenet of evacuation system design is to ensure that the available safe egress time (ASET) is longer than the required safe egress time (RSET). Measurement of ASET begins at the occurrence of a hazard. For example, at the time a fire begins burning or at the time flooding begins. RSET is measured from the time the order to evacuate is gIven.

This subtle difference underscores that the egress system is part of a larger safety system. If for a given hazard scenario there is a certain ASET, improvements in detection or occupant notification can be used to lengthen the ASET by giving the evacuation order earlier. A relative comparison of ASET and RSET is indicated in Figure 16.5.

Numerous studies have been conducted where people were interviewed who survived serious shore side fire incidents to gain insight into behavior during the fire. These surveys have shown that panic, as defined previously, is not observed even in severe fires with large life loss. The behavior, which is actually observed, is more accurately-described as *fear* or *anxiety* (8). Additionally, an emergency evacuation of a passenger vessel, which was pier side, was described as not exhibiting panic as defined above (9).

Many terms, which have been used historically to describe evacuation in shore, side codes and standards are beginning to work their way into shipboard requirements. Some of these terms are *egress, exit, exit access* and *exit discharge.* Means of egress is the term used to describe escape routes. An exit access is a path to an exit, an exit is a protected path, and an exit discharge is a path leading from an exit to a protected area such as a muster station, a survival craft embarkation area or an area of refuge. These terms are defined more completely in National Fire Protection Association Standards 101 and 30l.

16.5.1 Egress Route Design

SOLAS Regulation II-2/28-l.3, which was added following the sinking of several RO-RO passenger ferries, calls for an evacuation analysis *early in the design process.* This regulation highlights the importance of a well-designed egress system, and is intended to ensure that the egress paths are not simply fitted into available space after other areas of the ship are designed. Although this regulation only applies to SOLAS passenger vessels, the same philosophy should be applied to all passenger vessels.

Egress routes convey people from areas on a ship to protected areas such as muster stations, areas of refuge, and survival craft embarkation areas. Egress routes should be plentiful and wide enough such that the required safe egress time falls within the available safe egress time, configured such that they are protected and accessible, dimensioned

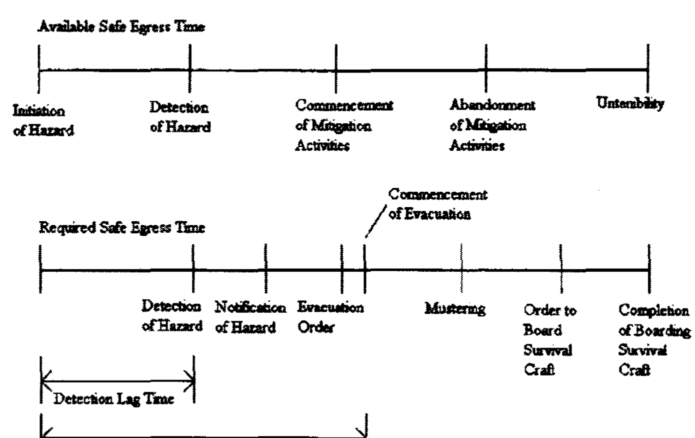

Figure 16.5 Comparison of ASET and RSET (Not to Scale)

is important to have adequate *muster* or *assembly* stations. These are the areas where passengers report when the alarm is sounded. There they are counted and instructed on what to do. Passengers will normally remain in the assembly station until the emergency is brought under control, or a decision is made to abandon ship. SaLAS requires that assembly stations provide sufficient clear deck space to accommodate all persons assigned to muster at that station, but at least 0.35 m^2 per person. Once the decision to abandon ship is made, passengers need to be directed quickly to the embarkation area where they will board a survival craft. For this reason, assembly stations should be close to embarkation stations, and in some ships the assembly stations and embarkation stations will be the same location. Assembly stations should provide reasonable access to several embarkation stations, so that the crew can have flexibility in loading survival craft.

16.7 EVACUATION

Assuming that direct transfer to another vessel is not possible, abandonment takes place via the survival craft, usually lifeboats and liferafts. Modern lifeboats are totally or partially enclosed craft, which are seaworthy and dry. They are the preferred method of abandonment in the open sea. Inflatable liferafts are usually arranged to automatically float free of a sinking ship, and they can be used on smaller ships that don't have room for lifeboats. Inflatable liferafts also provide an important part of the survival craft complement on most passenger ships.

The primary cause of death in disasters at sea is hypothermia, not drowning, though drowning is often the ultimate cause of death as a complication of hypothermia. Hypothermia is the lowering of body temperature through transfer of heat to a person's surroundings. Normal body temperature is 37° C, and human metabolism requires that excess heat produced by the body be transferred away from it. A naked human being is comfortable in air about 10° C lower than normal body temperature, or around 27° C. This is in the range where the body can easily maintain thermal equilibrium. As air temperatures get higher than body temperature, strategies such as sweating or fanning may be necessary to increase heat transfer to the surrounding air. As temperatures get lower than that at which thermal equilibrium easily can be maintained, shivering, a strategy, which increases metabolism, will begin. To avoid this unpleasant and ultimately unsustainable condition, humans wear clothes to provide insulation, trapping a layer of warm air next to the skin.

Water, however, transfers heat from the human body at a rate 25 times faster than air at the same temperature. For this reason, temperatures that would seem moderate in air are dangerously cold for long-term immersion in water. Temperatures that seem merely cold in air are immediately life threatening in water. Water-soaked clothing, and the action of waves, which flush water through loose clothes, hampers the maintenance of a warm water layer next to the skin. For this reason, survivors of a marine accident, which requires abandonment of the ship, must stay out of the water and as dry as possible, except in those situations where the water is relatively warm and rescue is close at hand.

16.7.1 Lifeboats

Modern lifeboats bear little relationship to the open pulling boats of just a generation ago. All lifeboats built today include permanent enclosures to protect the occupants from the sea and the hazards of hypothermia. Partially enclosed lifeboats are used on passenger ships (Figure 16.7). Their rigid enclosures include wide openings to enable rapid boarding. When the boats are underway, these openings can be shut with curtains of waterproof fabric. Cargo ships carry totally enclosed lifeboats, covered with a full rigid canopy and hatches, which can be, latched shut. On gas carriers, a pressurized air system is added to enable the boat to travel through toxic or explosive gas atmospheres for up to 10

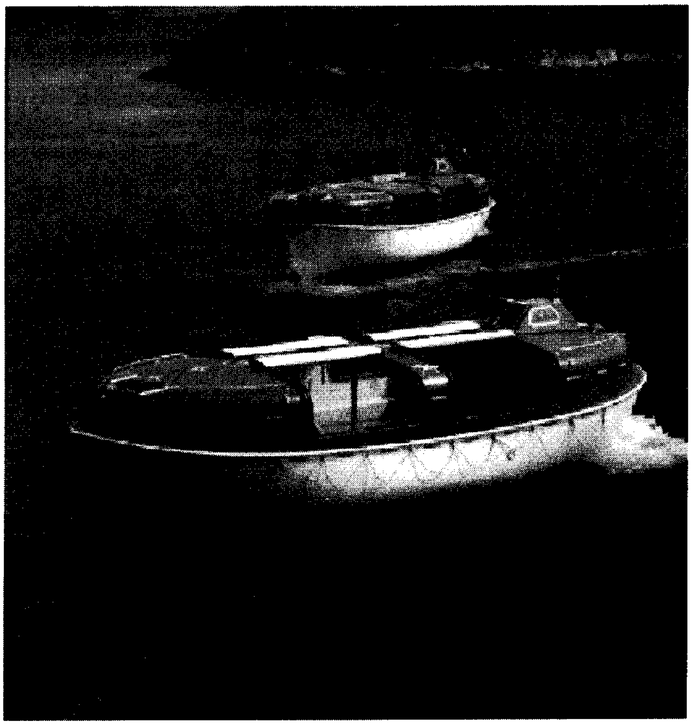

Figure 16.7 Partially Enclosed Lifeboat for Passenger Ships

minutes. On tanker lifeboats, in addition to an air system, a water spray system is added to protect the boat during transit through fire on the water.

Development of today' s lifeboats goes back to the 1960s, when the transportation of oil by ship grew dramatically, as did the size of the ships carrying the oil. Offshore oil exploration and development also expanded with the depletion of onshore oil reserves and the development of drilling rigs capable of operating in deeper water. Concern grew for the safety of a ship's crew in a casualty that ignited the cargo, or a rig's crew in a blowout and fire.

A number of countries began working on totally enclosed lifeboats that would be able to travel through fire on the water. After a number of designs were tried, the totally enclosed lifeboat made of fiberglass reinforced plastic or aluminum, equipped with an exterior water spray system and interior air supply system for the engine and occupants, was found to be the best solution (Figure 16.8).

These countries began to require lifeboats of this type on their tankers and drilling rigs. In the early 1980s, a complete revision of Chapter III (Lifesaving Appliances) of SaLAS made totally enclosed fire-protected lifeboats mandatory on all new tankers, starting in 1986. The framers of the new chapter recognized that the hypothermia protective benefits of totally enclosed lifeboats had the potential to save even more lives on ships where cargo fires were not a great concern.

As a result, totally enclosed lifeboats were required on all new cargo ships, and partially enclosed lifeboats were required on all new passenger ships starting in 1986.

The most modem and efficient launching systems for totally enclosed lifeboats allow boarding the boat at the position in which it is stowed, and launching directly from that position using a control that is operated from inside the boat.

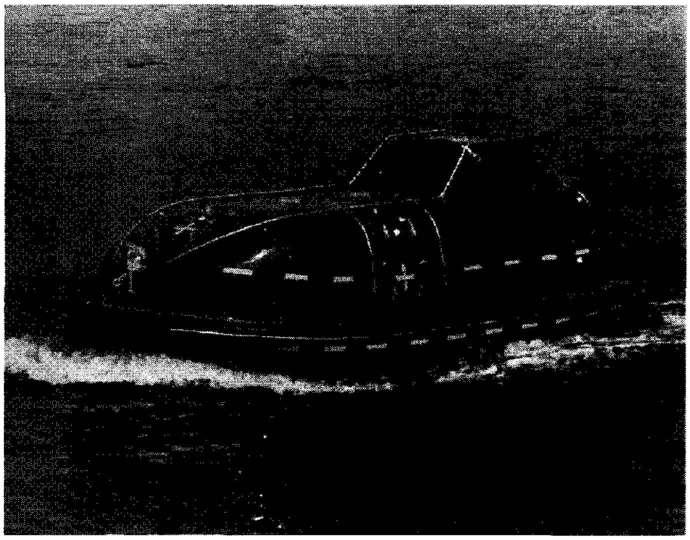

Figure 16.8 Totally Enclosed Lifeboat for Cargo Ships and Mobile Offshore Drilling Units

SaLAS Chapter III requires such a system on cargo ships and tankers. Lifeboats on passenger ships may need to be lowered an embarkation deck for loading, but once loaded, lowering of the boat is controlled from a position inside the lifeboat.

No longer is it necessary for the winch operator to stay on board a sinking ship in order to launch the lifeboat, then attempt to scramble into the lifeboat at the end of a long rope ladder.

The new SaLAS requirements also establish minimum launching speeds based on the distance between the deck and light waterline. These launching speeds may be as high as 1 mlsec. That's about twice as fast as many previous conventionallaunching systems, and is intended to prevent the lifeboat from being battered against the hull of a rolling ship as it is being lowered. In spite of improvements in launching systems, skillful boat handling is still required when releasing a boat in heavy seas.

16.7.1.1 Free-fall lifeboats

The risks with conventional lifeboat systems have been substantially reduced by the free-fall concept, which allows the lifeboat with its full complement onboard to be launched by falling freely into the sea. During the free-fall, kinetic energy is generated. This kinetic energy is used to propel the lifeboat away from the distressed vessel during and after water entry. The lifeboat moves away from danger even if the engine does not operate.

The first reference to a free-fall lifeboat was an 1897 patent issued to A. E. Falk of Sweden. The patent drawing depicts an enclosed lifeboat that can slide off the stem of a ship. The free-fall height was approximately three meters (12).

In 1939 Captain White ofthe Bay and River Navigation Company proposed the concept of a free-fall lifeboat (he called it a non-sinkable submarine lifeboat) to the Bureau of Marine Inspection and Navigation of the United States Department of Commerce. This concept was reviewed by the Bureau, which concluded that:

> His means of launching lifeboats appears to be inadequate and dangerous, and can in no respect be considered equivalent to the present method of launching such boats. [The lifeboat] would strike the water at a terrific speed and would cause considerable shock to the passengers.

Twenty years later, in 1959, a Dutch sea captain concerned about safety on board his ship approached Joost Verhoef about the possibility of building a safer lifeboat for evacuating ships. Verhoef was a yacht builder in Aalsmeer, Holland and founder of Verhoef Aluminium Scheepsbouw Industrie. He designed and tested a free-fall lifeboat that looked very much like a submarine. This lifeboat went into service on a ship in 1961. It had a free-fall height of about six meters and was made of aluminum.

The concept again lay dormant until 1973 when two serious ship disasters occurred. After these accidents, the Nordic maritime authorities commissioned the Norwegian Ship Research Institute to begin development of an improved lifeboat launching system. The result of this effort was a 10.3 m long free-fall lifeboat that was tested in Hardanger Fjord in 1976 at free- fall heights of up to 20 meters. The first manned launch from the stem of a Norwegian ship, the *MIS Tarcoola,* occurred in Oresundsvarvet Shipyard in 1977. This installation was formally approved in September 1978.

Today, free-fall lifeboats are manufactured in several countries by many manufacturers. A typical free-fall lifeboat is shown in Figure 16.9 during water entry. The materials used in the manufacture of the lifeboats include fiberglass, steel, and aluminum. Free-fall lifeboats are being actively marketed and are quickly gaining universal acceptance. Currently, free-fall lifeboats are in use on cargo ships, tankers, mobile offshore drilling units, and fixed production platforms. The heights of free fall range from approximately six meters on smaller ships to over 30 meters on fixed oil production platforms in the North Sea.

Despite their widespread acceptance on cargo ships, free-fall lifeboats have not yet been used on passenger ships. It is generally believed that sufficient free-fall carriage capacity cannot be provided and still enable safe launching of the lifeboats.

Also, it is generally believed that special training is necessary for the full safety of a free-fall lifeboat to be realized. As such, the focus of this discussion is free-fall lifeboats on cargo ships and mobile offshore drilling units.

The requirements of SaLAS Chapter III for cargo 9hips require that lifeboats having aggregate capacity for the total number of persons on board be placed on each side of the ship.

However, the regulation permits use of one or more free-fall lifeboats capable of being free-fall launched over the stem, with aggregate capacity equal to the number of persons on board. This provision effectively reduces by a factor of two the number of lifeboat systems that must be purchased and installed if free-fall lifeboats are used.

Installation space for free-fall lifeboats with adequate capacity for the number of persons on most cargo ships is readily available. As such, on cargo and tank ships, a single free-fall lifeboat typically is placed on the stem of the ship as shown in Figure 16.10.

For a free-fall lifeboat to be placed on the stem of the ship, the deckhouse needs to be located aft so that the lifeboat is accessible from it without having to pass through cargo spaces. The space beneath the lifeboat can be used for equipment and deck storage. to pass through cargo spaces. The space beneath the lifeboat can be used for equipment and deck storage. On some ships the swimming pool is located in this area.

When installed on mobile offshore drilling units and offshore platforms, the typical arrangement is different. The rules for these units do not permit a reduction in the number of free-fall lifeboats as compared to conventional lifeboats because of the nature of the structure and its operations. The lifeboat generally projects from the side of the facility as shown in Figure 16.11.

Often several lifeboats must be used to accommodate the number of persons on board the facility. When used in this

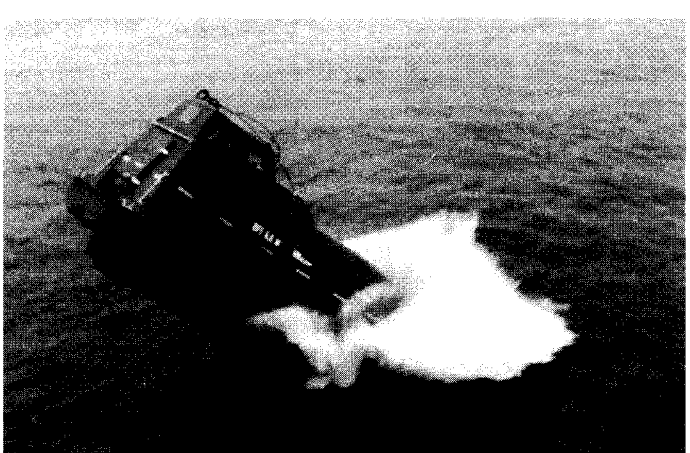

Figure 16.9 Free-fall Lifeboat during Water Entry

Figure 16.10 Free-fall Lifeboat Installed on the Stern of a Vessel

manner, caution must be exercised during launch so as not to have a boat free-fall into another boat that is already in the water.

16.7.2 Liferafts

Liferafts are unpowered survival craft. Although rigid liferafts exist, inflatable liferafts are by far the most common type, providing lifesaving capacity in a compact form. They do not replace lifeboats, but they do complement them. On cargo ships, liferafts arranged to automatically float free of a sinking vessel provide an opportunity for survival in the event a vessel sinks so quickly that the lifeboats can't be launched. Smallliferafts are also used at the ends of large ships remote from the accommodation spaces where the lifeboats are located, so that crewmembers in those locations have a survival craft readily available in case of a casualty. On passenger ships, some percentage of the lifesaving capacity can be provided in liferafts, and the rest in lifeboats.

When liferafts have to be boarded from a high freeboard location, some means must be provided to either lower a loaded liferaft from the embarkation deck, or else safely transfer the passengers from the embarkation deck to the liferaft on the water. Davit-launched liferafts, such as shown in Figure 16.12, are the conventional approach to this problem, but marine evacuation systems are becoming more common as shown in Figure 16.13. Davit-launched liferafts have a practical capacity limit of 25 to 35 persons. Larger liferafts are simply too hard to design so that they remain rigid when suspended and loaded to their full capacity. Since survival craft on passenger ships have to be launched within a 30-minute period, the practical limit for davit-launched liferafts is about six rafts per davit.

Marine evacuation systems consist of either a slide or chute system that convey passengers from the deck to a platform on the water, from which they can board liferafts on the water (see sec. 16.7.4). Since the liferafts can be dropped from their stowage locations into the water in an uninflated condition, they can be larger. A marine evacuation system can handle two to three times as many people in 30 minutes, as a davit-launched system requiring a similar amount of deck space.

Inflatable liferafts are required to be equipped with canopies to provide hypothermia protection for the occupants, and to prevent the liferaft from being swamped in waves. Ironically, as lifeboats have become enclosed as a rule, liferafts without canopies have come into wider use in recent years. These liferafts, shown in Figure 16.13, known as open reversible liferafts internationally, or inflatable buoyant apparatus in the United States, can be used in protected waters such as rivers or lakes, or even in coastal ocean wa-

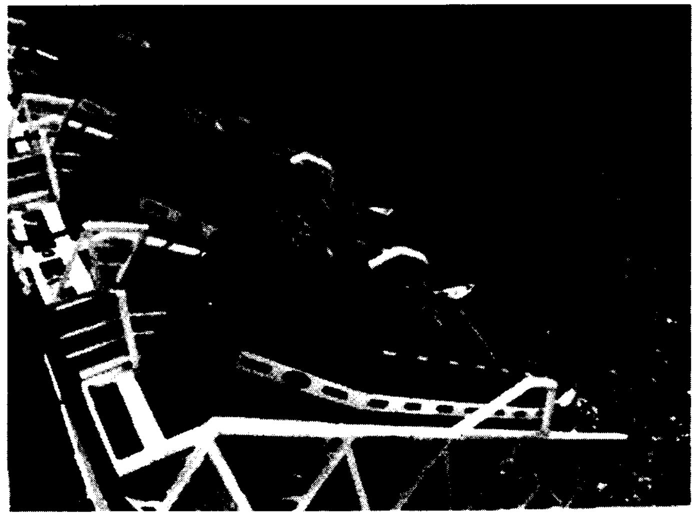

Figure 16.11 Free-fall Lifeboats Installed on Mobile Offshore Drilling Unit

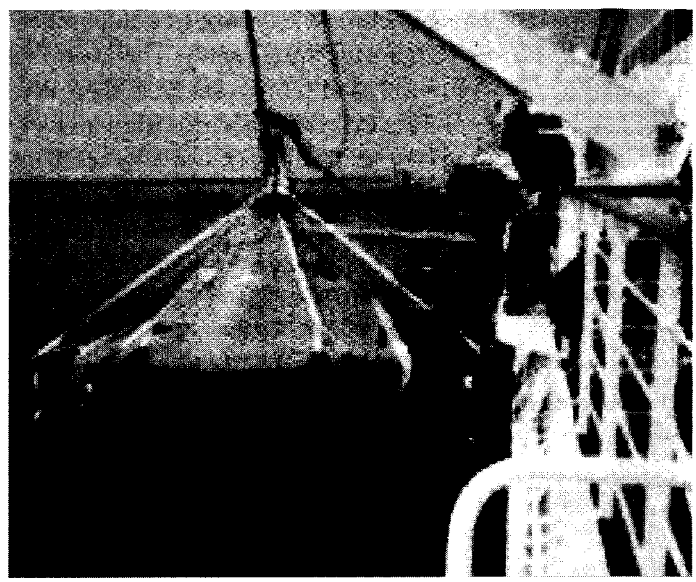

Figure 16.12 Davit-launched Inflatable Liferaft

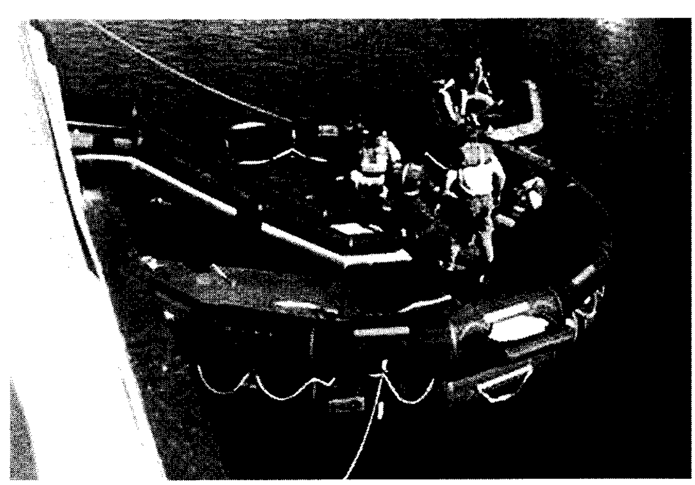

Figure 16.13 Open Reversible Liferaft (Inflatable Buoyant Apparatus)

ters where rescue is close at hand. The IMO High Speed Craft Code allows the use of these open reversible liferafts, but high-speed craft operations are limited, and operators must have a search and rescue plan, so that in the event that the high-speed craft has to be abandoned, rescue will come swiftly.

16.7.2.1 Liferaft Stability

The capsizing of the ferry, *Estonia*, in the Baltic in 1994 with the loss of over 900 lives raised some important questions about the adequacy of the life-saving systems in a rapid capsizing accident involving a roll-on/roll-off (RO-RO) ferry. The assumed 30 minutes evacuation time was not available for an organized abandonment. The few survivors that were able to make their way to the open deck had to jump into the water to escape the sinking ship. Inflatable liferafts floated free as the ship sank and although designed to inflate in the upright position, many of them had capsized, by the time people in the water reached them. There may have been several reasons for this, including capsizing by wind and waves, or inflation initiated under water rather than on the surface, as intended. Of the individuals who found their way to the liferafts, some may have been too weak to climb aboard. Others who were able to climb aboard found themselves on the bottom of capsized liferafts where they were still exposed to the cold water, wind, and waves. Some of those who managed to get to these liferafts died of complications due to hypothermia.

This and other casualties involving RO-RO ferries, including sinkings and fires, prompted IMO's Maritime Safety Committee to appoint a Panel of Experts to recommend actions to be taken to prevent such RO-RO ferry disasters in the future, or at least limit the number of lives lost. The Panel met and developed recommendations during the first half of 1995, and by the end of the year, an international SOLAS Conference had adopted a number of new SOLAS requirements for RO-RO passenger ships. A number of these resulted in new lifesaving appliances for ro-ro passenger ships, and a requirement for those ships to fit the new equipment over a five-year period.

SOLAS requires liferafts to be arranged so that one person can right them. Normally they have a righting strap fitted to the bottom of the liferaft.

Seafarers are trained to understand that capsized liferafts can be righted. However, in a rapid capsize accident, trained crewmembers will not always be available. Cold and disoriented passengers would have difficulty in the first place understanding that the liferafts were capsized, or furthermore, in understanding how to right them. Ultimately, the SOLAS Conference adopted a requirement for RO-RO passenger ships to carry liferafts be of a type that would either be reversible, or would automatically self-right if capsized before they could be boarded.

Automatically self-righting liferafts have a hull form, which is generally oval or elliptical in form. Inflated arch tubes, which support the liferaft's canopy, are much higher than on conventional designs. The canopy can either be stretched over the arch tubes, or suspended from them. In either case, the high arch tubes make the liferaft unstable in the capsized position, causing it to turn right side up should it be capsized for any reason.

Reversible liferaft designers have more options in the way they meet the requirements. One design provides a second canopy on the *underside* of an inflatable liferaft. The floor of the liferaft is suspended between two main buoyancy tubes, rather than on the *bottom.*

Another type of reversible liferaft has two main buoyancy bodies with sidewalls between them surrounding the passenger space. On the water, one of these buoyancy bodies serves as the floating hull, and the other as the top of the liferaft. This design seems to simplify some of the design problems posed by the dual canopy concept, but at the price of higher weight and an increased inflation gas charge.

16.7.3 Rescue Boats

A rescue boat is designed to perform man-overboard rescues, assist other ships in distress, and to tow liferafts short distances in order to move them away from danger near the scene of a casualty, and to gather them together to await rescue. Figure 16.14 shows a typical rescue boat.

Rescue boat requirements were introduced into SOLAS in the 1983 amendments, in recognition of the fact that not

Figure 16.16 Chute-type Marine Evacuation System and Reversible Liferafts

used for aircraft evacuation have been around for years, but in marine applications were troublesome in high winds and heavy seas. When the surface of the slide got wet, it could be extremely slippery, leading to very high speeds. When the unfortunate person on the slide hit the inflated platform at the bottom of the slide at high speed, they could be catapulted right over the side and into the water. These designs were perfected in the mid-1990s. They are stable in high winds and seas, and the surface of the slide is a mesh material, which does not absorb water, and allows any water hitting the slide to drain through. At the bottom of the slide, there is an open inflatable platform. Crew members on deck drop the liferafts to the water near the platform, while crew members on the platform inflate the rafts and secure them to the side of the platform for boarding. Because these liferafts are not designed to be suspended from a hook with a full load of people on board, there are fewer design limitations on liferaft size. Liferafts to hold 50 people are now available, and larger sizes are possible. With a dual track slide and large liferafts, one manufacturer expects to be able to handle 500 people in 30 minutes.

A conference on escape slides and chutes, in Japan in January 1991, marked the beginning of the development of marine evacuation system (MES) standards eventually adopted by IMO in 1996. Today, MESs not only include inflatable slides (Figure 16.15), which can currently be used from as high as 25 m above the waterline, but also vertical chute systems (Figure 16.16). This is a tube of fabric, which hangs vertically from the embarkation deck to the inflatable platform floating on the water. The launching and loading of liferafts are handled from the inflatable platform just as with the inflatable slide. The chute itself contains either a series of funnel-like structures, or loose folds of fabric inside an outer sleeve.

The evacuee's drop into the opening at the top of the chute, and the interior structures control their descent to a safe speed until they reach the opening at the bottom on the platform. These can be used for heights of 25 m or more. They were originally developed as escape systems for high-rise buildings. One chute system is approved for 400 people in 30 min. Double-track slides are capable of similar capacities.

An MES requires about as many crewmembers to operate as a davit-launched raft installation, but can handle two to three times as many people. There are advantages in the water, too, since 50 person, 100 person, and even larger rafts can be used. Therefore, fewer crewmembers may be needed to supervise the rafts. Even so, on many high-density services, catering staff and, sometimes even, concessionaires are needed to fully man the survival systems. Since 1986, SOLAS has allowed persons specially trained in liferafts in lieu of lifeboatmen to operate and supervise the liferafts.

16.7.5 Survival Craft and Rescue Boat Requirements

Table 16.IV summarizes the international survival craft and rescue boat requirements for different types of ships and mobile offshore drilling units (MODUs). The requirements for ships come from SOLAS and the MODU requirements from the IMO 1989 MODU Code. Percentages refer to the total number of persons permitted on board.

16.7.6 lifejackets and Immersion Suits

In addition to *primary lifesaving equipment* (lifeboats and liferafts), ships are also required to carry *personallife-saving appliances,* designed for the use of only one person at a time. SOLAS requires lifejackets for everyone on board, plus additionallifejackets to accommodate children, crew who are on watch; those who rely on remotely located survival craft, and arrangements where the basic allowance of

TABLE 16.IV International Requirements for Survival Craft and Rescue Boats

	Lifeboats	*Liferafts*	*Rescue Boats*
Cargo ships (incl. Tankers)	100% capacity each side or 100% free-fall stern-launched	100% capacity float-free (on ships with free-fall lifeboats, the liferafts must be served by launching appliances or marine evacuation systems)	One (May be a lifeboat if the boat meets all lifeboat and rescue boat performance requirements)
Passenger ships	70% capacity, evenly distributed on either side or for short international voyages only—30% capacity, evenly distributed on either side	Sufficient capacity to ensure, that together with the lifeboats, 125% capacity in survival craft is provided. Liferafts must be arranged for float-free operation and be served by launching appliances or marine evacuation systems	One on vessels under 500 tons gross tonnage, two on all other ships
Additional requirements for RO-RO passenger ships	—	Liferafts must be self-righting or reversible	Rescue boats must be *fast* rescue boats with motion-compensating launching appliances
MODUs	Sufficient to ensure that 100% capacity is available if all of the lifeboats at any one location are lost or rendered unserviceable	100% capacity float-free	One (May be a lifeboat if the boat meets all lifeboat and rescue boat performance requirements)

Note: Source SOLAS Convention for ships, IMO MODU Code for MODUs.

lifejackets may become inaccessible. The 1983 SOLAS Amendments included new standards for lifejackets, which have resulted in an increase in buoyancy for many designs, and in improved performance for most. Subsequent refinements to the performance requirements in the 1996 SOLAS Amendments and the LSA Code have further improved the ease of donning of lifejackets.

SOLAS provides standards for inherently buoyant lifejackets, inflatable lifejackets, or a hybrid of both. Inherently buoyant lifejackets use foam, kapok, or other low-density materials for buoyancy. Inflatable lifejackets rely entirely on gas-filled chambers to provide buoyancy. Hybrid lifejackets provide minimum inherent buoyancy that is supplemented by inflated chambers. Inflatable and hybrid lifejackets must have established maintenance programs. Alllifejackets have retro-reflective markings and individuallights attached to them to make it easier to find survivors in the water at night. They also have whistles attached so that persons in the water can signal to rescuers.

Rescue boat crews and those assigned to assist evacuation at marine escape systems are at high risk of exposure to cold. Passengers and crew alike rely on these crewmembers to affect rescues and coordinate evacuations. Lifejackets do not provide as much exposure protection as do immersion suits or thermal protective aids, which are specifically designed to minimize the loss of body heat. SOLAS recognizes this, and requires that vessels have immersion suits or anti-exposure suits available for these crewmembers. Vessels that operate solely in warm climates (between 32 degrees north latitude and 32 degrees south latitude for U.S. vessels) are exempt from this requirement.

Lifejackets and immersion suits must be stowed in readily available locations. That means passengers and crew should have easy access to them somewhere along the way from their accommodations or work spaces to their muster areas. Immersions suits, adult lifejackets, and child lifejackets must all be stowed separately, and the stowage spaces marked accordingly. Since inflatable and hybrid lifejackets are designed to be deflated when stored, they take up less space than inherently buoyant ones.

16.7.7 Life Buoys

Life buoys are the immediate means to provide buoyancy to a conscious person overboard. Thus, life buoys should be stowed in a way that allows for rapid deployment on any open deck that extends to either side of the vessel, and at. least one buoy must be located at the stem. Life buoys should not be attached to the vessel in any way. SOLAS requires that two should be stowed so that they can be quickly released from the navigating bridge without striking the vessel when released. Common attachments that aid in locating and rescuing persons in distress are self-igniting lights, self-igniting smoke signals, and buoyant lifelines.

16.7.8 Alerting and Locating

Ships in international service carry satellite Emergency Position Indicating Radio Beacons (EPIRB). These EPIRBs start broadcasting a distress signal automatically when they are thrown into the water or when they automatically float-free from a sinking vessel. Satellite EPIRB signals are picked up by U.S. and Russian polar-orbiting satellites, and relayed to ground stations which can identify the ship and its location from the EPIRB's digital signal. This EPIRB provides position information so precise that rescuers can fly directly to the scene. When help is close by, the parachute flares carried on the bridge can alert potential rescuers to a ship in distress, or can help rescuers locate the ship more quickly, especially at night.

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CHAPTER 17

Structural Arrangement and Component Design

Bart Boon

17.1 INTRODUCTION

The design of a ship starts with determination of the vessel operational characteristics (see Chapter 7 - Mission and Owner's Requirements), its main dimensions (see Chapter 11 - Parametric Design), the general layout, and the hull shape. But it really becomes a ship only after all of this is translated into actual components that can be fabricated **in** the shipyard. The translation of a general design into structural components is the genesis of the structural design of a ship.

The design of the structure of a ship, or an offshore bottom-mounted or floating platform, is a complicated process. However, the structural designer can benefit from the experience of other designers and classification societies. **In** the past it consisted of two steps:

1. design of the structural arrangement, and
2. the derivation of the scantlings (sizing of the structural components).

Until recently most scantlings were based on simple classification rules, even when these rules were based on significant analyses and research. Today the trend is toward calculations based on first principles and modem computing tools. However, the decisions on the structural arrangement are still human-based even if they have been embedded **in** an expert system. Steps 1 and 2 are still followed, except that the preliminary determination of structural component scantlings is derived primarily from a rule-based spreadsheet provided by the classification society. Steps 1 and 2 are then followed by further steps such as structural first-principle analyses, finite element modeling and analyses, etc. (see Chapter 18 - Analysis and Design of Ship Structure and Chapter 19 - Reliability-based Structural Design). Most classification societies have structural analysis systems that they make available to the designers using their rules (see Chapter 8 - Regulations and Classification Requirements). Finally, there are today a number of research developed structural optimization programs (see Chapter 18 -Analysis and Design of Ship Structure).

In the past, most naval architects received instruction and practice for steps 1 and 2 and were thus able to complete the structural design of ships. Today, they are given little instruction or practice in steps 1 and 2; instead they receive a generic engineering education **in** structural analysis. This has resulted in specialization where practical designers develop the structural arrangement and structural engineers perform the structural analysis for the designer-prepared structural arrangement. This is very inefficient.

This chapter attempts to reintegrate the separated parts, but it will focus mainly on step 1.

The structural design process involves choice of the construction material, the location, shape and dimensions (scantlings) of the plates and profiles used. This is followed by analysis of the structure arrangement to establish that it will perform its functions **in** a satisfactory way and possibly to optimize shapes and dimensions in order to reach the best result possible **in** economic and/or technical terms.

Obviously when setting up the design of a ship's structure it is important to realize what the function of the various components may be. And that can be other than the commonly considered role of providing strength and stiffness. Although the various functions can be of equal importance, emphasis in design and analysis work, and also in the presentation in this chapter, is generally on strength and stiffness.

For many years fulfilling that structural role led to more or less standardized structural components. Many details found in ships built in the early 20th century are basically similar to some still used today (disregarding for a moment the impact of the riveting to welding change). For many common details those described by Stiansen in the 1980 edition of Ship Design and Construction (1) can still be used.

Several recent developments make a revision of the chapter in reference 1 desirable. First of all new types of ships have entered the shipbuilding industry in rapidly increasing numbers. Also, jack-ups, semi-submersibles and single-point moored production vessels in the offshore industry are now an important part of the units to be designed by the naval architect. The variation in transport ships may even be more rapidly evolving as is shown in high-speed catamaran ferries, heavy cargo float-on float-off ships, vessels with specialized cargo handling systems, etc. They place requirements on the structural design not thought of before. All of these vessel types are characterized by the fact that the traditional simple beam as a representation of the ship hull is n~ longer adequate. New materials such as steels with a high yield strength (HYS), aluminum and fiber reinforced plastics (FRP) offer new possibilities for structural concepts to the designer. Combining this with new fabrication techniques resulted in new components such as steel sandwich panels. All of this is combined with a continuous improvement of the analysis methods leading to minimization of the structural weight and/or the fabrication cost. This, however, also leads to failure mechanisms becoming important for the structural design that were far less so up until recently, such as fatigue and buckling. Finally an intensified concern for safety of people and protection of the environment has had its impact on the structural design of ships. All of this necessitated the writing of the present chapter and adding *structural arrangement* to its title.

This justification for writing the present chapter has already made it clear that the emphasis in its contents has changed when compared to that of the previous edition. The large variety in possible details leads to a generic approach to structural design where understanding the functioning of the various components is attempted rather than trying to present a comprehensive description of all structural components of the ship. For that type of description reference 1 can still be used. Many other books and journals show details as used in present-day ships. In particular the books by Smolla (2), Taylor (3) and Eyres (4) give many details used today in the more common ship types such as container ships, tankers and bulk-carriers. Much can be learned from damages that occurred in practical use of ships. Mano et al. (5), the Tanker Structure Cooperation Forum (6,7) and lACS (8) describe many failures and the repairs/improvement of the failing structural details.

17.2 STRUCTURAL ARRANGEMENT DESIGN

Step 1 is still required today before any of the other steps can be started. Also as structure is a large weight component, the structural scantlings are required as soon as possible to enable the structural weight to be calculated. Fortunately, the structural arrangement design can start as soon as the principle characteristics, preliminary general arrangement and compartmentation are decided. The exact location of the major structural components is decided by the general arrangement designer.

Therefore, the general arrangement designer should be aware of the impact of his decisions on the structural arrangement and must take into account such requirements as:

- frame spacing,
- web frame spacing,
- minimum double bottom depth based on classification society requirements, and
- other similar requirements.

Many decisions on main structure placement, such as peak bulkheads, double bottom, double sides, longitudinal bulkheads, etc., are defined by law.

Fortunately, the structural arrangement of typical ships has been established over time and is a good starting point for new designs. It is only where departures are made from the proven approach for new ship types or offshore structure that there is a need for original development and tradeoff analysis when preparing a ship's structural arrangement. However, even with this good start, there is still a lot of opportunity to develop production friendly/cost effective structural arrangements. Vice versa there is still the risk of preparing bad structural arrangement design.

The structural arrangement designer has to decide the following characteristics while developing the structural arrangements (some of which may have already have been decided by the general arrangement designer):

- spacing of main transverse and longitudinal bulkheads,
- width of side tanks,
- tweendeck height(s),
- hatch width,
- deadrise,

- bilge radius,
- tank compartmentation,
- single or duct keel,
- molded line (plate/stiffener orientation),
- connection details (brackets),
- longitudinal/stiffener to web frame), etc.

Many structural arrangement details, including the assembly and block definition, are developed as standards for a shipyard and will be documented in the shipyard's *Shipbuilding Policy* (see Chapter 14 - DesignlProduction Integration).

Section 17.10 presents examples of structural arrangement and components. It should be clear that the structural arrangement designer and the structural engineer (if not the same person) must be members of an integrated design team. Neither can operate independently of the other, otherwise there is a risk of an adverse outcome involving extra effort for reworking the design (sometimes called iteration) and longer design development time. Integrated product teams (IPTs), integrated product and process development (IPPD) and concurrent engineering (CE) are approaches that attempt to ensure that such isolation and its resulting adverse impact on design and construction do not occur (see Chapter 5 - Ship Design Process).

17.3 GENERAL APPROACH OF STRUCTURAL DESIGN FOR STRENGTH AND STIFFNESS

Already in the earliest stages of the design of a ship, structural components appear in the drawings. The shape of the shell is shown, position and overall dimensions of transverse bulkheads are fixed, and the layout of the accommodation dictates the location of its partitions. All of this generally is determined without explicitly having in mind the design of the structure itself. In the early design, the structure only implicitly plays a role by an estimate of the structural weight (generally including a choice of the main material used) and the location of its center of gravity. Sometimes structural considerations may playa role for instance in the choice of the exact location of bulkheads. In reference 5 the position of the bulkhead between the tank part of the hull and the engine room is decided such that the still water bending moment is minimized. Vessel types for which structural considerations playa decisive role in the design, such as jack-ups, exist, but are exceptions. Characteristics of the structure that have less relation to aspects of the general ship design, such as plate thickness, stiffening systems and detailed shapes are not normally part of the early ship design.

The structural design process commences by recognizing those characteristics that already were defined in the general ship design. The structural designer must be aware of the reasons why each structural component exists, or the function it has in the ship. A choice of the material will be made if this has not already been done in the first stages of the design. Additional structural components, which must be provided, such as web frames, stiffeners, etc., will be considered. This includes a decision on structural arrangements, such as longitudinal versus transverse framing. Basic decisions such as stiffener spacing or web depth will be made. All such decisions will mostly be based upon experience of the designer, earlier built ships of similar type and general rules and regulations laid down by classification societies. For less common ship types first decisions will be taken on additional strength bulkheads, bracing systems for semi-submersibles and other special structural members.

Subsequently simple first analyses will be made to decide upon initial structural member dimensions or confirm those that were already assumed based upon experience, hand estimates or classification rulebook. It is necessary to make such initial analyses because without those no further analyses based upon more sophisticated methods are possible. The simple analyses in this situation for instance will use only water pressure in combination with stiffener spacing to decide upon initial plate thickness. This can be done from simple formulas as given by classification societies or with elemental formulas from engineering mechanics. In the latter case it is sometimes difficult to decide the allowable design stress.

Only when the conceptual design of the structure, that is the structural arrangement, and a first estimate of its dimensions (scantlings) is available, can a more thorough analysis of loads and responses be made. A full description of this analysis is given in Chapters 18 - Analysis and Design of Ship Structures. Such analyses may be used in order to optimize the structural design and to give a final all-encompassing assessment of the structural reliability. In general such analyses are not needed (and should not be used) for setting up the structural arrangement and conceptual choices.

17.4 FUNCTIONS OF STRUCTURES AND THEIR COMPONENTS

The structure of a ship and hence the structural components exist because they have to fulfill certain roles for the vessel as a total system. Many different functions are possible and often a component must perform more than one role simultaneously. The roles include:

- provision of hull shape in order to comply with the selected main dimensions, stability and resistance characteristics. Generally very little input is possible for the structural designer, although developable hull forms and even hull forms consisting of flat plate elements have been used in view of reducing fabrication costs,
- watertight envelope and subdivision (shell, watertight bulkheads, tank bulkheads),
- oiltight subdivision (tank bulkheads),
- gas tight subdivision,
- functional subdivision and separation (cabin bulkheads, store bulkheads, etc). Mostly these components have to perform sound and heat insulation roles at the same time as their separation function, must have a nice appearance etc. Therefore elements fulfilling these roles often consist of materials different from that used for the main hull construction such as described in reference 9,
- fire subdivision (galley walls, blast bulkheads in offshore units),
- noise and vibration insulation,
- provision of aesthetics (funnel, cruise liner superstructure) ,
- corrosion allowance or allowance for mechanical deterioration, wear. This generally is not provided as a separate component, but as an increase in thickness over that necessary for the normal function of the component. With the growing use of direct calculations instead of rule-based design a separate treatment of this sort of thickness increase has become more essential.
- load introduction (concentrated or distributed),
- load transmission from one point (area) to another,
- load transfer from one structural component to an adjacent one: connections and joints (brackets),
- reduction of local stresses (stress concentrations),
- provision of stiffness to prevent buckling (stiffeners, tripping brackets, bracket flanges),
- provision of stiffness to prevent deflections (load ramps, mechanical systems), and
- provision of stiffness to reduce vibrations.

Still more roles are possible such as shown by structural components of which the dimensions are chosen based upon the effect in view of regulatory requirements. Coastal vessels in Holland in the past had extra deep web frames because gross tonnage, and hence manning requirements and harbor duties, were based upon the volume within the inner side of the frames. Similar considerations still playa role today in the U.S. as illustrated by the framing chosen for the high-speed ferry Tricat (10).

Most structural components will have to play several of those roles simultaneously. Even when that would not have been the case to start with, it may be the result of the other roles. For instance once a plate structure has been decided upon for the funnel out of pure aesthetic grounds, itS-very existence requires that it must be strong enough to withstand loads resulting from wind and ship motions whilst at the same time the structure must be stiff enough to prevent local vibrations.

Important as the other roles may be, the present chapter will concentrate on the last seven of these functions, that is, those related to strength and stiffness of the structure. Often only these functions are meant when structural design is discussed. Incorrect as that may be from the point of view of importance of the various functions, it certainly is true that the strength and stiffness function more than the other functions, needs attention to be properly explained and taught.

17.5 MATERIAL SELECTION, INCLUDING MATERIAL FORMS

Often the main material for the hull structure is not explicitly chosen. For most vessel types it will be steel without any further consideration. Only the grade of the steel and sometimes whether or not high-strength steel will be used is an explicit decision in the design process. Other materials such as aluminum or fiber reinforced plastic (FRP) also often are chosen as natural for the subject type of vessel and as the obvious material for the shipyard in view of their normal production process. In other words, very often no explicit choice of material is made.

The material of components generally is the same as the main material for the hull, but sometimes different materials are chosen based upon particular considerations. For example the material for liquefied gas tanks can be aluminum because of its good toughness at low temperatures when compared to steel.

In situations where a choice between several materials can be made the first consideration will be how suitable each material is for the function considered. The gas tank just mentioned is an example where only a limited possibility exists for alternative materials. In other situations fabrication cost or lifetime cost are the main dictating considerations. Lifetime cost includes cost for repair, maintenance and operational costs for fuel and additional payload resulting from a different hull structure weight. Other aspects may be availability and delivery time for the material during construction and when repairs may be needed, behavior in damage situations (reserve strength), appearance (for yachts), etc.

A comprehensive discussion of various materials may be found in Chapter 20 - Hull Materials and Welding and Chapter 21 - Composites.

17.5.1 Mild Steel

Ever since the end of the 19th century mild steel is the ubiquitous material for constructing ships. Obviously it is a material that offers many advantages. It is cheap, easy to work, light (at least when compared to its predecessor, wood), available everywhere, is quite forgiving with respect to quality deficiencies during fabrication and small damages during operation, has a good reserve strength after serious damage has been sustained and repair of steel structures is easy. It is the material that will be used whenever there are no special reasons to use an alternative material.

Steel characteristics were improved over the years in order to obtain better material properties such as notch toughness in order to reduce the risk of brittle fracture, which had caused many ship losses in, and after, World War II. Ship construction, in particular welding, was made easier by refining the material's microstructure, for instance, in Thermo-mechanical Control Process (TMCP) steel.

Special steels were produced which have special characteristics. Stainless steel is less susceptible to corrosion and attack of various chemicals. In Japan. special steel has been developed with improved crack arresting properties at low temperatures.

17.5.2 High Yield Strength Steel

For many years steels have been used with high to very high yield strength, say 320 to 700 MPa. Also ultimate strength generally was higher, but not to the same amount as yield strength. This characteristic was mainly obtained by increasing the amount of carbon in the steel and special heat treatment by the steel manufacturer. It meant that the steel had to be pre-heated for welding with higher fabrication costs for the ship as a consequence. Also other properties of the steel were negatively influenced, such as its notch toughness. Application was limited to special situations, as for naval ships where low weight was important and the disadvantages ofHTS (high tensile strength steel) were acceptable. In terms of tons used the even more important application was in very large ships such as tankers and bulk carriers. Use of normal strength steels led to plate thickness that were no longer practical in the fabrication process in the yard. High-strength steels were a solution to that problem. Recently the TMCP process (see section 17.5.1) is used for fabrication of high yield strength steels as well. The cost of welding this material is substantially less than for the older high strength steels. At the same time other disadvantages of such steels also reduced such as its low notch toughness. Taking into account the reduction in weight and in weld content the use of TMCP high strength steels in many cases is hardly more expensive than the traditional steels or may even be cheaper. As a consequence recent years have seen a rapid increase in the use of these steels, also in vessels where it was not used hitherto.

An introduction to the various high-performance steels and their welding is given in reference 11.

17.5.3 Aluminum

Aluminum is a material that has similar or only slightly less strength than traditional mild steel but with a specific weight that is about one third. This is the main reason for using aluminum. Other advantages are better mechanical performance at (very) low temperatures (such as the tank for liquefied gas mentioned earlier), better corrosion resistance and a nicer appearance. Its main disadvantage is its cost, both for the basic material and for its fabrication. Other disadvantages are the special workmanship required for fabrication, less general availability in some places, deterioration of mechanical properties after welding, more weld deformation, its relative fatigue-proneness, and risk of corrosion when in contact with steel.

Like steel, aluminum is available in plates and sections. Design and fabrication of aluminum structures is generally similar to that of steel, albeit with differences in detail. Sections are produced by a different method, that is, by extrusion rather than rolling. This process allows complex section shapes, including hollow ones that may be specifically designed for a special application. An example is the use of extruded profiles for helicopter decks, where the profile combines plate and stiffener and sometimes even tubular lines for fire fighting. Use of such profiles reduces fabrication cost, improves fabrication time and gives a better finish to the end product (remains more flat).

Example 1–The use of extruded aluminum profiles. Figure 17.1 shows a deck constructed using extruded aluminum profiles. Note the incorporation of anti-slip ridges and special edges of the section allowing easy fit up and welding. Further examples are shown in Figure 45.39.

The material used for producing plates and that for sections differ in their metallurgical content and the heat treatment used in the fabrication process. Different material behavior follows. Extruded sections are less suitable to be used in direct contact with seawater and therefore are used mostly inside the hull or in decks.

In the past the main connection method for aluminum was riveting. This was replaced by electric fusion welding

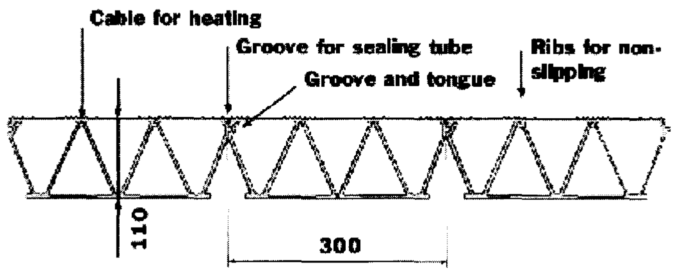


Figure 17.1 Extruded Aluminum Profiles Used for a Deck

some time ago. Some modern welding methods are particularly suitable for aluminum and offer interesting new possibilities for the structural design. Laser welding makes it possible to weld through the thickness of the plate thus allowing designs that with traditional welding could not be fabricated because of inaccessibility (see examples given in section 17.9.4 on sandwich panels). Friction stir welding (FSW) makes welds of a much smoother appearance and a better mechanical strength after welding.

This process presently is used mainly for pre- fabrication of large deck panels assembled from a series of extruded profiles.

As with steel, aluminum also has seen metallurgical developments that significantly raised the strength both of the parent material as well as after welding. Such materials presently are available in plate form only, not in extrusions. When using high-strength aluminum, fatigue becomes even more of a main issue in the structural design than heretofore.

Summarizing: aluminum is mainly used where weight is at a premium such as in high-speed craft (whether motor powered or sailing). Another important application is in the superstructures of ships that have a high center of gravity like cruise vessels. In gas tankers aluminum is used for tanks because it remains notch-tough even at very low temperatures.

More information on the use of aluminum in ships can be found in Chapter 44 - Catamarans, in books such as reference 12 and in proceedings of conferences such as reference 13.

11.5.4 Fiber Reinforced Plastic (FRP)

A widely used material nowadays is fiber reinforced plastic (FRP). A comprehensive description of this material and its applications is given in Chapter 21 - Composites. The material consists of reinforcing fibers of glass, carbon or similar embedded in a polyester or other matrix. Such structure is light compared to steel and relatively cheap in fabrication. The weight advantage becomes much more pronounced when the composites are used as skins of a sandwich with an even much more lightweight core (see section 17.9.4 on sandwich panels). Generally fabrication makes use of male or female molds, which adds to the cost of the end product. This effect is somewhat reduced when the molds are used to produce a series of craft. Small sailing boats therefore are often built in plastics. Luxury yachts use composites because they can be shaped very easily in complex three-dimensional forms such as in superstructures. Special high-strength fibers and corresponding matrix materials are used in high performance racing yachts, whether sailing or motor driven. Other advantages of composites are the smooth finish, not very prone to damage, good reparability and easy to be maintained.

Disadvantages are the generally poor fire properties including the danger of emission of noxious gases. Specialized companies and techniques are needed for fabrication. In some places in the world repair may not be easy given the skills of the available local work force.

11.5.5 Concrete

Concrete has been used for building ships during the two world wars in the 20th century. The main reasons for the use were shortage in steel supply and the possibility to employ workers, companies and building sites not already involved in building (steel) ships. Since then the material has been promoted on and off. Some recreational craft used it mainly because of its cheap fabrication and because it needed very little maintenance. In the 70s and 80s several fixed offshore oil and gas production platforms used concrete as its construction material. Again fabrication and maintenance cost were major considerations, but in this case an added advantage was the high weight as the platforms were gravity based (see Chapter 43 - Offshore Drilling and Production Vessels, Figures 43.18-43.20).

In summary the advantages of concrete as a structural material for ships are its low fabrication cost, its ,general availability, the workforce employed in the fabrication needs not to be very highly skilled, the material is non-corrosive, hence the maintenance costs are low, the constructional details are not very fatigue-prone, it can withstand low temperatures, and sometimes the high weight is an advantage (such as to reduce motions in floating oil production systems, FPSOs).

Notwithstanding this last statement structural weight of concrete in general is considered to be a major disadvantage. The development of high-strength and thus (relatively) low-weight concrete holds some potential in this respect.

Although concrete is used very little, its potential is recognized over and over again. In particular this is so for stationary applications such as in FPSOs (in particular for gas) and very large floating structures as airports and the mobile offshore base (MOB). But even for ships is sometimes is considered a viable alternative (14).

11.5.6 Wood

For millennia wood was the ubiquitous material for small boats and large ships. It was generally available and could be worked well with the tools then available. The 19th century saw its replacement first by iron and then steel. The main reasons were that the wood supply in Europe, became somewhat exhausted, vessel sizes grew, wood structures could not easily comply with the concomitant increased strength requirements, and finally it was found that structural weight and space were considerably less for steel than for wood.

Wood continued to be used for smaller vessels for a long time and in many parts of the world it still is an important shipbuilding material today. In mine sweepers wood was long preferred because of its non-magnetic properties but now it is replaced by fiber reinforced plastics and non-magnetic steels.

Today the main application of wood is in recreational craft, often in combination with plastics. Sometimes (balsa) wood is used as core material in sandwich structures with composite or aluminum skin plates.

11.5.7 Titanium

Titanium is as strong as, or even stronger than steel and as light as aluminum. Its strength-to-weight performance is probably best of all structural materials available for ships today. But the material is extremely expensive. Its use for structures, therefore, is confined to very special applications. Naval and civil submarines for deep diving depths may use titanium alloys (see Chapter 55).

11.5.8 Basic Structural Material Configuration

The structural material as delivered to a shipyard generally consists of plate, profiles, pipe, forgings and castings. For certain materials they can be *extrusions* (aluminum) or *pultrusions* (FRP). Plate can be smooth or with a raised pattern on one side such as *diamond plate.* It can also be *expanded* by a process that cuts slits in the plate and thep pulls it apart to expand it.

Figure 17.2 shows typical profiles that are used in shipbuilding.

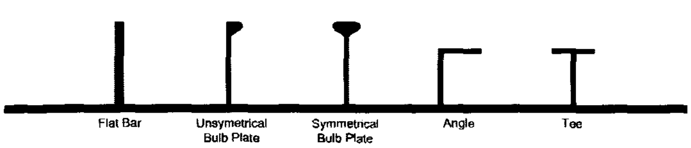


Figure 17.2 Shipbuilding Profiles

17.6 THINKING IN STRUCTURE MODELS

A ship, even the simplest one, is a very complex structure consisting of many different parts connected in various ways. This structure must be capable of accepting a large variety of loads, static, dynamic, as well as transient. If not adequate or loaded in an accidental way the structure may fail in many different modes.

Structural design must result in a vessel that reliably can cope with all those different aspects. At the same time the resulting design must be economic to build, operate and maintain and it may have to comply with still other requirements.

It is obvious, therefore, that the structural design process itself is complicated. It starts from some elementary outlines as given in the operational specification of the vessel and its preliminary design (see Section 17.3 and Chapter 5 - Ship Design Process).

In the early stages of the structural design many decisions must be taken by the designer that determine the concept of the structure. Decisions taken in this stage are to a large extent the main factors for the adequacy of the end result in technical, safety and economic terms. As shown later (example 6 of the brace system of a semi-submersible in section 17.7.5) incorrect decisions may not become obvious until when, in a further stage a detailed numerical analysis of the structure is undertaken. Or, worse still, the incorrect decision even then, may not become obvious and an unnoticed non-optimal structure will be the result. The main help the structural designer can get in this stage is from his know l-edge about structural and material behavior, his insight, his experience, and example ships (see the structural descriptions in the ship type chapters in Volume II). Descriptions of actual damage cases are most instructive. See for instance papers like references 15 and 16 or books like references 5, 6, 7 and 8. But important above all is the capability of the designer to look upon and think about structures and their behavior a systematic way. To that end a structure must be modeled in the mind (think models). Basically it is the same way in which structures are modeled when analyzed using standard mechanical engineering approaches as described in textbooks like (17). In general think models remain fairly simple. Beams, simple plates or trusses with a variety of end conditions are often used to represent (parts of) the complex structure of a ship. In actual structural analyses such models do have a limited accuracy but for setting-up conceptual designs this kind of models generally serves its purpose. Finite element models used in analysis will increase the accuracy of the result, but are not needed when designing the concept of a structure. However, the pictorial representation of finite element analysis results often may be quite helpful in training the mind to recognize possible behavior and failure modes of a structure.

The think models continuously change with regard to their viewing position. At one moment the complete vessel is considered as a beam loaded over its length (as in the traditionallongitudinal strength assessment). The next moment only the deck is considered as being the upper flange of such beam. That flange then may be considered as a plate loaded in its plane by tension or compression. This, for instance, allows the study of stresses around a deck opening on the basis of stress concentration factors around openings in simple plates. Such zooming in and zooming out in models is essential in setting-up the concept for any ship structure.

Fundamentally this is possible as an application of *St. Venant's Principle* stating that the influence of a local disturbance at some distance is independent of the details of that local disturbance. In this case it means that the effect of a deck opening is restricted to its vicinity and that the overall response of the hull (the beam representing the hull girder) is not influenced by that deck opening.

17.7 TRANSFER AND TRANSMISSION OF LOADS

17.7.1 Equilibrium of Loads

The well-known Newtonian principle that action equals reaction states that any force (or moment) exerted upon a structure will be in equilibrium with another force (or moment) having the same load line, being of equal amplitude but having the opposite direction. The reaction force can be a concentrated force, a distributed force (such as water pressure) or a virtual force. The latter is the case when the structure under influence of an external load starts to move as a rigid or flexible body. In that case the reaction force is an acceleration force loading the mass just as gravity forces albeit with a different direction and magnitude.

Example 2-A point-to-point load. A shuttle tanker moored to the stem of a floating production unit (FPSO) exerts a load to the stem of the FPSO hull because of current forces (see Figure 30.7 in Chapter 30 - FPSOs). A reaction force coming from the single point mooring system near the bow of the FPSO unit counteracts this load.

Example 3-A point to distributed load. The vertical load of a heavy load placed on the deck of a transport barge (see Figure 49.23 in chapter 43 - Heavy Lift Ships) results in an increase of draft and a change in trim of the barge. This in turn results in a change in water pressure over the bottom of the barge such that the integration of that distributed extra load is in equilibrium with the weight of the load placed on the deck.

Example 4-A distributed to distributed load. A wave exerts a distributed load over the immersed part of the hull of a cargo vessel. This load results in rigid body linear and rotational accelerations of the hull. Each mass particle of the hull under influence of the accelerations will exert a force on the ship, which, when combined, together represent the reaction force to the wave action force.

Note that in the above examples sometimes it is obvious which load to call action and which reaction. In other examples this is less so. In general there is no need to call a load either action or reaction. Both are possible and the decision should be based upon the situation under consideration.

17.7.2 Force Transmission and Transfer

The previous section discussed how any load exerted on a ship is in equilibrium with a reaction load. It can be said that the load is transmitted from the point of application to the point where the reaction force is exerted (note that the points of action and of reaction may be considered vice-versa as mentioned in the previous section). Under influence of that load the structure will show a response in the form of stresses and deformations as dealt with by mechanical engineering. It means for instance that if the structure would be sectioned at any point the total (internal) force resulting from the distributed stresses is in equilibrium with the (re)action force.

A ship structure is a complex assembly of many components and basically all of them participate in the force or load transmission. The series of components taking part in the transmission of a load generally is called the *load path.*

Example 5-A load path. For example 3 given in the previous section the load path may be as follows. The module weight is transferred via special foundations into the web frames of the barge. They transfer that load via the vertical webs into the shell plating and the longitudinal bulkheads. The shell plating distributes the force over all bottom transverses, which in turn redistribute the load over all bottom longitudinals. These finally transmit the load to the bottom plating where the load is in equilibrium with the local additional water pressure resulting from the change in draft (under influence of the exerted module load).

The load path thus consists of many different components and the forces must be transferred from one component to another. Generally this occurs via local welds connecting the two components. Note that the word *transmit* is used to indicate how a load is brought from one point to another point that is spatially located elsewhere. The word *transfer* is used to describe how a load is brought from one structural component into another, something that basically occurs at one location. This distinction between *transmit* and *transfer* is adhered to in this chapter but, it should be noted, it is not generally accepted.

Also sometimes specific structural components may serve to transfer loads from one component to another. The bracket connecting a deck beam to the vertical frame on the shell serves to transfer the load. At the same time such bracket may be seen as a component transmitting a force from one side of the bracket to the other. Again this is a matter of modeling where one can zoom in (load transmitting component) or zoom out (transfer element between horizontal and vertical web).

As can be seen in the example of a module onboard a barge the load path is not always unique. In the given case there is not only one bottom transverse and one bottom longitudinal, there are several of them. They form parallel load paths that together transmit the load from one point to another. There is no need that all parallel load paths transmit the same percentage of the total load. How much will go through one and how much through another is an important matter in Subsection 17.7.5.

17.7.3 Ways of Load Transmission and Beam Theory

A structural component can serve to transmit a load (force or moment) from one point to another (or several other points or a distribution). Often these points are the ends of the component or member under consideration. If the member is a beam such transmission can be in various forms: tension, compression, bending, torsion or a combination. Note that different forms may exist at the two ends, for example, a moment at one end and a force at the other end. Engineering mechanics show how such loads are related and the relevant formulas will not be repeated here (see Chapter 18 - Analysis and Design of Ship Structure). For simple beams the relation depends solely on the magnitude of the loads and the overall dimensions ofthe beam (not on its cross sectional properties).

Also from engineering mechanics it is known that such a beam will deform under influence of the loads. The relative position and orientation of the two points of load application changes. The magnitude of the displacement and/or rotation of one point relative to the other depends on the load type, the dimensions (in particular the length) of the beam and its cross sectional properties and on the material composing the beam. If that deformation is large the beam is called flexible. Conversely, if the relative deformation is small, the beam is stiff. Formulas to relate the beam deformation to the loads exerted may be found in many standard books on engineering mechanics such as Gere and Timoshenko (17).

Whenever a virtual section across a loaded beam is considered, internal forces and moments and stresses and strains resulting from these can be distinguished. Internal forces and moments and deformations at any point of the beam are related to each other and in general can be found by integration of loads and stresses and strains over the beam length and over its cross section as applicable. All together this is called the beam theory in engineering mechanics. Standard textbooks such as reference 17 deal with this extensively. For the present chapter it is assumed that the reader is completely familiar with this beam theory.

Beam theory gives, by far, the most important think model used by the designer of ship structures. It is used both for small components of the structure such as a deck beam as well as for a ship's hull in totality. It is important to note that the theory is based upon certain assumptions concerning the behavior of the beam under load. The designer must be fully aware of the following assumptions:

- cross sections remain plane under load and perpendicular to the neutral axis,
- cross sections remain undeformed under load (their shape does not change), and
- the magnitude of the bending stresses is linearly related to the height of the point under consideration in the cross section.

Later in this chapter it is shown that this is not always the case. Such situation may have a major impact on the structural design. This is so for instance when an open ship is loaded in torsion and prevention of warping (deformation of the cross section) is one of the ways to accommodate the torsional load (see section 17.10.6).

From the general formulas in beam theory the following aspects may be derived of which the designer of ship structures should be well aware, especially as these characteristics often are the first ones dictating the structural design:

- a beam loaded in tension provides the stiffest (or least flexible) transmission possible. The stiffness in compression is the same, but may soon reach a limit in case of a slender beam when the buckling strength is reached,

- a beam in bending is far more flexible than one in tension; the flexibility increases with the third power of the beam length when transfer of a concentrated load is considered or even with the fourth power of the length when a distributed load exists. **In** bending, the smaller of the upper and lower flanges is dictating for the stiffness, but even more important is the web height, which contributes with its square,
- shear lag and the resulting effective breadth may reduce the effectiveness of the flanges in particular for short beams (see Chapter 18 - Analysis and Design of Ship Structure and reference 18),
- when loaded in shear mainly those parts of the beam are effective which are parallel to the plane in which the shear force works. Often this will be the web plate of a beam. The stiffness then is directly related to the cross sectional area of that (web) plate and linear with the length of the beam,
- the flexibility under shear and under bending for a beam depends on the ration between beam height (depth) and length. According to reference 5 the contribution of shear and bending will be about equal if the ratio is around 14. For shorter beams (which is normal for ships), shear flexibility governs and for longer beams, bending. Yet in practice bending is more commonly considered than shearing,
- when loaded in torsion a closed cross section is effective; an open cross section is **in** general very flexible when loaded in torsion, and
- the end conditions of the beam, whether free, simply supported, clamped or flexibly supported have a large impact upon the internal forces and moments and upon the resulting deflections. Whenever thinking in models, good insight as to the end conditions and their effect is essential.

17.7.4 Load Transmission Through Plates

The previous section discussed load transmission through structural components that can be modeled as beams. The other important way of load transmission is by means of plates or structures that may be modeled as plates.

A plate is characterized by two dimensions (length and breadth) that are large compared to the third dimension, the plate thickness. Two ways of load transfer exist, in-plane forces and out of plane (lateral) loads. In-plane moments (that is around an axis perpendicular to the plate) translate into in-plane stresses which are unevenly distributed over the plate surface. Out of plane moments (around an axis in the plane of the plate) are closely related to lateral forces, as will be seen. Because of their relative thinness, plates are much stiffer for in-plane loads than for lateral loads.

For the transmission of lateral loads the plate may be considered to act as a series of parallel beams of rectangular cross section with a height equal to the plate thickness:.The transverse load will translate into bending moments just as is the case with ordinary beams. **It** is important to note that generally the structural concept will be such that lateral load transmission by plates is limited to a relatively short distance, say typically never more than 30 times the plate thickness. Otherwise the deflection of the plate and the bending stresses developed would become unacceptably high. More details are given in section 17.9.1.

A plate sometimes transmits in-plane loads just as a beam transmits tension or compression forces. **In** that case the stresses are equally distributed over the cross section of the plate. Similarly a plate may transmit an in-plane bending moment by a linear stress distribution over its (then necessarily limited) width. So far the plate behaves like a beam. An essential difference however is the possibility of a non-linear stress distribution. This will occur whenever discontinuities are present leading to stress concentrations, shear lag etc. The best illustration is by means of stress lines as described in section 17.9.2. Note that in beams non-linear stress distributions may also exist, but normally they are disregarded.

Generally plates carry lateral loads through bending and in-plane loads by in-plane tensile and compressive stresses as described. However **in** some situations lateral loads may be carried by in-plane membrane stresses. This may be the case when deflections of the plate are large relative to the plate thickness or when the plates already initially possess a deformed shape (see section 17.9.5).

17.7.5 Series and Parallel Load Paths: Stiffness and Deflection

The previous section explained that the structure transmits forces from one point to another. This may be done in various forms such as through bending, tension, or torsion. The examples given in the previous sections show that a load path might consist of several components each transmitting the load in a different way. The total deformation of the load path is the sum of the individual deformations of its components. The flexibility is the relative displacement of one end to the other, including the so-called tail effect, divided by the applied load. The tail effect means that the deformation of one element influences the displacement of the end of an attached component, which is rigidly connected to the first one. For instance, rotation of the end of one element makes the next element rotate, hence its end displaces, even when that second element does not deform itself. **In** summary, a load path may be considered to exist of several load paths in series (compare to electric circuits) and is characterized by the total flexibility being the sum of the individual flexibilities.

Similarly a structure may offer more than one load path in parallel.

Example 6-Load transmission in a semi-submersible. A semi-submersible consists of two lower pontoons each supporting one or more columns that in turn support a box-like upper platform as shown in Figure 17.3. A decisive type of hydrodynamic load for this sort of structure is the so-called splitting force. This is a pair of forces working on the inside of the two pontoons, trying to push them apart. Note that the total splitting load on the structure, as a whole, is zero. Similar to the splitting load there is a squeezing force, that is, a load acting on the pontoons from the outside inwards. Such load generally is less onerous for the structure. The vessel structure will transmit the splitting load from one pontoon to the other. A tubular brace as indicated is the obvious structural design and will directly transmit the load as a beam in tension. Omitting the brace in a think model will immediately show that a second load path uses bending of the columns and the upper platform (and loading the upper platform in tension at the same time). From the general observations regarding beam theory it will be clear that this alternative load path is far more flexible than the one offered by the direct brace connection. Of course when the brace is part of the structure the alternative load path also exists and has to deform in the same way as the first load path through the brace. For that deformation, only a small load is needed. Both load paths attract load. However, the stiffer load path carries more than the flexible one. The total load is distributed over the two paths in relation to their stiffness.

From this example a very important aspect of structural

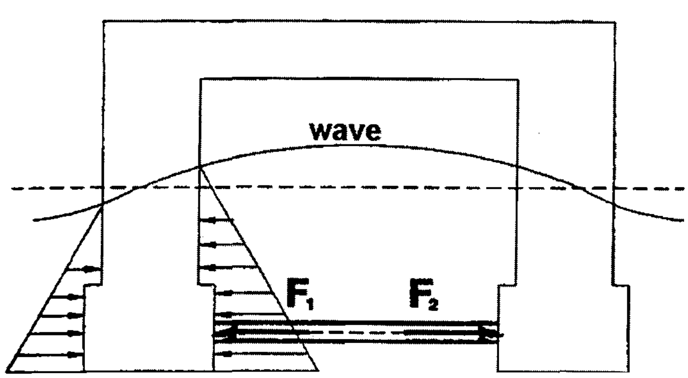


Figure 17.3 Principle of a Brace in a Semi-submersible

design becomes clear. That is, when alternative parallel load paths exist, the stiffer ones carry most of the total load. The load is distributed over parallel load paths in direct relation to their respective stiffness.

The model of the example shows that without braces the total tension force and the bending moment in the upper pontoon are fully determined by the magnitude and location of the splitting force. If those are accurately known, the internal forces (including moment) in the upper pontoon are completely determined. It does not say anything of the distribution of those internal forces over the complete structure of the upper pontoon. In structural design, often the integrated internalloads of a beam are completely determined but the actual distribution is not. Sometimes the distribution of the stresses may be fairly accurately estimated. For instance, consider the same semi-submersible model now with brace system. The total tension force over a cross section of the complete model (including both upper pontoon and braces) is the same as before. However, the distribution over brace and upper pontoon depends, as mentioned, on the relative stiffness of the two load paths. From that it can easily be seen that nearly all the tension force will be accommodated by the brace; only a small proportion will go through the upper pontoon. If the latter must be estimated, the stiffness or flexibility of the two load paths must first be estimated with the help of the formulas from beam theory.

Note that this example is also a good illustration of think models. Here the cross section of the semi-submersible is thought of as a two-dimensional series of beams. The fact that in the actual structure more than one parallel brace will be provided is not visible in the think model. Neither is the fact that at each lower pontoon probably more than one column is constructed. The model as presented serves one purpose: to be able to take a decision on whether or not to provide a horizontal brace system. To that end a number of braces and columns may be lumped into one brace and two columns. If other aspects ofthe structural concepts must be studied, different models are needed, each adapted to the question under consideration.

Example 6 also shows that the upper pontoon will transmit a bending moment and a tension from one side of the semi-submersible to the other. In order to establish the roles of deck and bottom (single or double) of the upper pontoon in this load transmission, different think models will be necessary. Note that a total tension force may be found in, for instance, the bottom plate of the upper platform. This tension results from both the total tension force that is present in the upper platform and from a tension force corresponding to the bending moment in the upper platform. Such tension force will not be distributed equally over the full *width* of the plate (which width in this case would correspond to the, probably longer, length of the upper pontoon). Shear lag and effective width ofthe plate (see section 17.9.10) play a role where the loads are transmitted from the columns to the upper pontoon. In order to study these effects it will be necessary to think of the upper platform or its component deck or bottom in terms of a flat plate.

17.7.6 Superposition and Decomposition of Loads and Responses

The formulas for beam and plate behavior given in standard textbooks all show that the response of a structure in the form of deflections, deformations and stresses is linearly dependent on the magnitude of the applied load. Implicitly this has been used already when describing alternative parallel load paths, as in example 6 in the previous section.

For linear systems the response to the sum of various loads is equal to the sum of the responses to the individual loads. This fundamental property of linearity is important in setting up and analyzing ship structures. It means that the response of a structural item may be determined by summing the responses to individual loads. In the example 5, considering the load path of a module weight on the deck of a pontoon to finally the water pressure on the bottom plating, all structural components not only participate in this particular load transmission, but in many others at the same time. In particular this is so for major parts of the hull structure such as the shell plating and longitudinal bulkheads. The stress component resulting from the example load transfer is only a small part of the total stress in the shell plating. The same holds true for the water pressure load on the bottom plating, which is the sum of many vertical loads on the total vessel. Adding all those vertical loads is the same process that traditionally is used to determine the draft and trim of the ship. It means that the total water pressure on the bottom structure can be determined far more easily from such an integral calculation of the vessel than from individual load paths. Taking all of this together we may conclude that in general no need exists to analyze load paths completely over their full length. Generally the analysis is performed only up to the point where the stress (or deformation) of a particular load represents a small portion of the total stress in a component. The support for the module on the deck of the transport pontoon will be analyzed up to the point that its effect on the local stresses becomes small. Mostly this is until the load is distributed over the shell and longitudinal bulkheads, and, for bending, over the deck and the bottom of the barge (or ship). Similarly the total load on the bottom structure may be considered as load input independent of the details of all the loads they originate from.

The hull structure consisting of decks, bottom, shell, longitudinal bulkheads and transverse bulkheads, plays the main role in redistributing vertical, horizontal and torsional loads over the length of the vessel in order to equalize them with the hydrostatic and hydrodynamic loads acting on the ship. This hull structure is often called the backbone of the ship, or the hull girder. The analysis of this total structure is called the overall strength analysis. The local strength analysis covers the load path from its application point to the backbone, or even a shorter path for details. The possibility to superpose and decompose loads and responses is fundamental in making conceptual decisions for a ship structure and allows a fairly accurate analysis without necessarily modeling the complete ship. In doing so the designer and the analyst must be aware of the assumptions that underlie this approach such as linearity and beam theory. The designer must be aware that deviations from these assumptions often occur and he must be able to judge when this implies that more refined calculations and assessments may be necessary. In the present chapter several examples are included to show when this may be the case.

17.8 FAILURE MECHANISMS AND STRUCTURAL OBJECTIVES

A limit exists for the magnitude of the loads that a structure can carry. Beyond that limit the structure will fail. The structural designer must be well aware of the various failure modes that may exist and how to prevent them. The designer must design in such a way that the possibility of failure for the final structure under the anticipated loads will be kept at an acceptably low level. The way in which this can be analyzed is described in Chapters 18 - Analysis and Design of Ship Structures and 19 - Reliability Based Design, but before that, at the stage of the first setting up of the structural design, recognition of the failure modes will have a major impact. The exact level of safety is less important for the structural concept than awareness of the various failure modes themselves.

The failure modes are directly related to the kind ofload to which the structure is subjected. Tensile forces may lead to rupture of the structure when the tensile strength of the material is surpassed. But before that a limit may sometimes already be reached with the yield strength. This may result in unacceptably large deformations of the structure. That is, unacceptably large in view of safety (infrequent), operability (in particular where the structure has to interact with mechanical systems) or nice appearance. For the structural concept it is less important in general whether the failure would be the result of exceeding the ultimate strength or the yield limit; in any case, it would be in tension.

Generally, in view of the safety margin the allowable stress would probably be related to yield strength. Safety against failure under tension usually requires sufficient cross sectional area. In exceptional cases the material and structure behavior after yield will playa role in the concept. This is for instance the case where redundancy after failure of a member is important (see subsection 17.9.8) or where a structure is designed for its behavior after damage (see subsection 17.12.3 for an example).

In compression a limit may be reached when yield or ultimate strength is exceeded. But more common is that a structural component under that load will fail due to overall or local buckling. More than cross sectional area, overall and local stiffness (moment of inertia) and the end conditions (clamped, simply supported, etc.) of the structural component are important.

Also excessive shear loads may lead to overall or local buckling. Shear stresses may be the result of simple shear forces in plates as well as stemming from torsion loads in open or closed cross sections. Books such as reference 19 clearly describe buckling of beams and plates.

Vibrations generally may be prevented by sufficient overall and sometimes local stiffness. It may even be necessary to install additional stiffeners, struts or pillars just to prevent vibrations by changing the natural frequency of the structure.

Sometimes the role of structural elements is not to carry loads directly but to assist other components in doing so without failing. Stiffeners to prevent buckling are a clear example of this. This shows that the structural designer must be fully aware of all the failure mechanisms that may take place in a structure and of the impact any failure may have on the overall reliability of the structure. This leads to a distinction between component failure and global failure. Questions are important such as whether component failure is progressive and leads to global failure on short or longer notice and whether structural redundancy exists (see Subsection 17.9.8). The designer must rely upon his knowledge and experience and that of others such as classification societies. In the conceptual design phase assessing the risks is qualitative. A quantitative assessment may take place later by a full probabilistic approach such as described in Chapter 19 - Reliability Based Design. Note that this conceptual knowledge in prevention of structural failure and risk assessment is different from the often-used assessment on the basis of for instance allowable stresses. The latter has many implicit assumptions regarding failure prevention that the structural designer must recognize explicitly.

17.9 CONCEPTS OF STRUCTURAL COMPONENTS

17.9.1 Laterally Loaded Plates

Without any doubt the most typical structural component of a ship is the transversely loaded plate. The watertight envelope of the vessel, the shell, consists of that type of structure and so do many other components such as tank bulkheads.

The plate transmits the lateral load from the points of application (which often are distributed over the full area of the plate) via bending to the plate support, generally a stiffener. A two-dimensional situation is where an infinitely long plate panel of limited width is supported at two sides by stiffeners. Already from symmetry considerations it will be clear that the load path may be considered as a series of parallel elementary beams of width ~x. Each elemental beam acts as any standard beam and complies with the beam formulas provided by the use E / (1 - y2) with y being Poisson's ratio instead of the normal Young's modulus E. This is because contraction of the elementary strip is prevented by the adjoining strips (20). From considerations of symmetry and anti-symmetry it follows that the elementary beams are simply supported by the stiffeners in case the beam stops at those supports. If beam and loading continue beyond the stiffeners the support may be considered to be clamped. A continuous beam with non-continuous loading behaves in an intermediate way.

Note that the maximum bending moment in the plate increases with the square of the distance between the supports (its unsupported span). In order to accommodate the same maximum bending stress the section modulus needs to be increased, which means increasing the plate thickness in direct relation to the unsupported span. In other words the desire for minimum weight of the structure will lead to the use of a small unsupported span. On the other hand the desire for minimum fabrication costs will lead to a reduced number of stiffeners and hence increase the stiffener spacing. Experience shows that a stiffener spacing ranging from about 0.5 meter for small ships to 1.0 meter for larger ships generally seems to be optimal for normal situations.

Consider a square plate supported by stiffeners at all four sides. From symmetry considerations it will be obvious that the load at, say, the center point of the plate will be transmitted equally to all four supports of the panel. In other words the load path to one support will carry only half the load it would carry in the two-dimensional case. Because of linearity of the system it follows that the responses of the plate panel to the loads will also be half of what it would be in the two-dimensional case.

If the panel is not square the distance of its center to one support will rapidly increase compared to the distance to the other support. From beam theory we see that the flexibility between the two load paths increases to the fourth power with that distance. The shorter load path rapidly attracts the major part of the total load transfer. This is completely in line with the earlier statement that stiffness attracts load. The aspect ratio *a/b,* of a panel length *a* and width *b,* determines the behavior compared to that of an infinitely long plate. Already for an aspect ratio of 2 the results both for maximum deflection and for bending moment in the plate are different only to a few percent from that for the infinitely long plate. For conceptual design normally we can think in terms of the two-dimensional case, as the aspect ratio of plate panels generally will be well above 2 (see also subsection 17.9.7).

The results for the two-dimensional and for the square panel are fully in line with the full plate theory as given for instance in Chapter 18 - Analysis and Design of Ship Structures or in Hughes (18).

17.9.2 In-plane Tension of Plates

As mentioned earlier a distinctive feature of plates loaded in-plane is that the magnitude of the stresses is not always linearly distributed over the length and width of the plate. Stress concentrations and shear lag will occur wherever there are discontinuities in the shape of the structure or in sudden changes in the applied load. Practical aspects of stress concentrations and shear lag will be dealt with in Subsections 17.9.9 and 17.9.10.

The stress distribution in a plate can be conveniently visualized by stress trajectories, also called stress lines. These are lines, which at each point of the plate are parallel to the direction of the principal stresses in that point. The distance between the stress lines is related to the inverse ofthe magnitude of the principal stresses. Note that basically two orthogonal sets of stress lines exist in any plate representing the two major stresses. Figure 17.4 shows the stress lines around a circular hole in a plate. Clearly visible is the stress concentration. With post-processors combined with finite element calculations it is easy to get an impression of the stress lines in an analyzed plate by plotting the direction and magnitude of the two major stresses in the centers of any of the elements as in Figure 17.5 from Reference 35. Often for clarity only one of the two sets of stress lines is represented. It can be shown that the stress lines in a plate are similar to the non-rotational flow of a fluid through a channel with the shape of the plate and any openings like small islands. This hydrodynamic analogue is a useful think model when designing a plate structure.

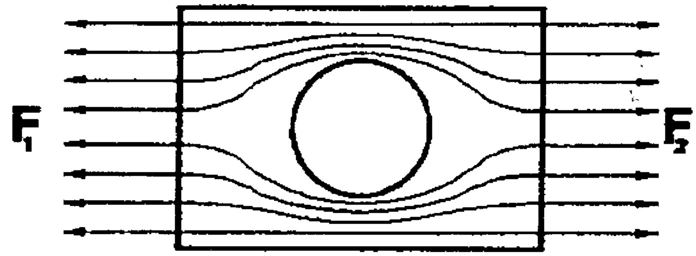


Figure 17.4 Stress Lines Around a Hole in a Plate

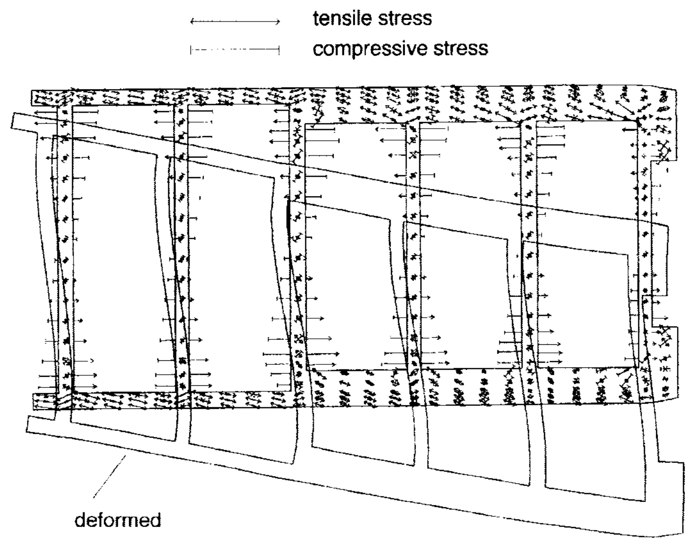


Figure 17.5 Major Stresses Around Hatch Openings in a Container Ship

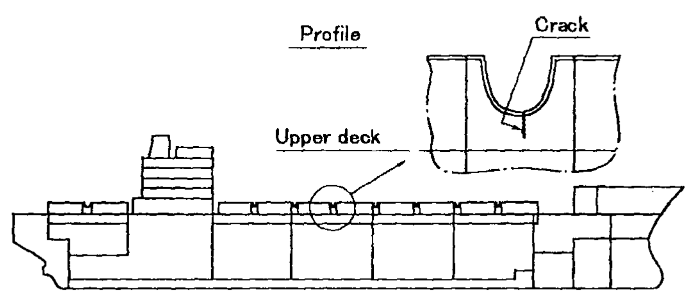


Figure 17.6 Hatch Coaming Continuity

Example 7-A hatch coaming. The hatch side coarning cannot be continuous over its full height (as would be preferable) between the hatches of a container vessel because of passage of pipes, etc. The optimal shape from a variety of solutions is shown in Figure 17.6 from (5). This result was found using finite element simulations. But the hydrodynamic analogue makes this obvious even without detailed calculations. Use of that analogy obviously can help to decide upon alternatives that are worthwhile to be investigated further.

Failure of plates in tension may be the consequence of local excess of the ultimate strength of the material, but more general, is the result of fatigue. A small localized crack generally is no problem strength-wise (unless this results in spill of oil or ingress of water into the hull) because local yielding will allow the structure to deform. Repeated loading will lead to crack growth until the crack reaches its criticallength. Assessment of such situations is the domain of fracture mechanics. For the structural designer it is important to realize that structural steels in general are rather forgiving with respect to local damages and small stress concentrations and that this may have an impact on the conceptual design.

17.9.3 In-plane Compression; Plate Buckling

When in-plane stresses are compressive the situation is completely similar to that with tensile stresses till the moment that plate buckling occurs.

Buckling starts when the structure becomes unstable, that is, when the plate deflection may take on any non-zero value. This is comparable to the situation where a column starts to buckle under a compressive load. However, once initial buckling has been reached, the load on the plate may continue to increase without getting *infinite* deflections. This is typical for plate buckling; it is not so for buckling of a column (often called Eulerian buckling). It makes plate buckling generally less onerous than column buckling, and therefore, in exceptional cases sometimes acceptable.

Example 8-Buckling in the side of a superstructure. The window openings in the side of the superstructure of a small ferry showed a situation where buckling occurred (which could be expected using the hydrodynamic analogue as just described). However, the load could further increase without endangering the safety of the vessel. After the buckling took place other parts of the structure (parallel bulkheads) took over the load-carrying role and the problem was mainly aesthetical. If the subject plate would not have been visible possibly the buckling would have been acceptable. However, if many load reversals take place (putting the vessel from a hogging into a sagging situation and vice versa) the buckles will be stretched again and thereafter buckle again. In such situation a risk of initiation of fatigue cracks exists. How long this situation can be accepted is a separate discussion, but generally such cracking is considered unacceptable.

Note that plate buckling may be the result of compressive stresses as well as of shear stresses (after all, this involves compressive stresses under 45°).

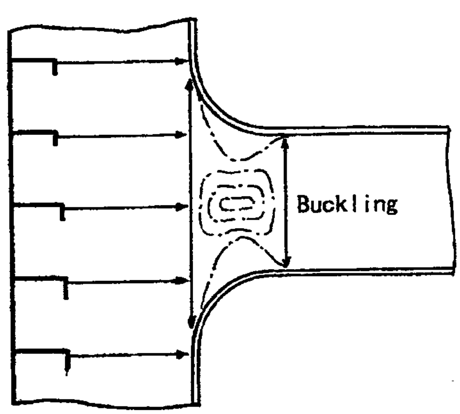
The general way to prevent buckling is to add buckling stiffeners preferably (but not exclusively) in a direction parallel to the compressive stress. The amount of stiffeners and their spacing follows from the general theory on plate bu~kling as described in Chapter 18 and in other referenced books.

Example 9-Buckling of a tanker cross tie. Buckling occurred in the crosstie of a tanker as shown in Figure 17.7 from (5). The tie obviously could not transmit the horizontal transverse load without buckling. A simple additional stiffener parallel to the load at half height of the tie, possibly only over the wider part of the web plate, might have prevented this damage. In this situation the damage will not immediately impair the vessel reliability but repeated loading alternating between tension and compression could result in fatigue cracking. The crack probably would grow relatively quickly and lead to a situation that is dangerous for the vessel.

Free plate edges are particularly sensitive to buckling. Edge stiffening generally is provided to prevent this whenever the unsupported width of the free plate exceeds something like *30t (t* being the plate thickness). Note that such edge stiffening may easily be confused with a faceplate provided to accept tensile (or compressive) stresses. Sometimes such stiffening may play both roles at the same time.

17.9.4 Sandwich Panels

In Subsection 17.9.1 the behavior of laterally loaded plates was discussed. The plate bends under influence ofthat load and experiences stresses which are linearly distributed over its thickness. From this it is obvious that the extreme fibers ofthe plate (those at its surfaces) play the major role in accommodating the bending moment. The effectiveness of



Buckling due to compression

Figure 17.7 Buckling of a Tanker Crosstie tear-off ofthe skin from the sandwich, punching ofthe skin plate by a concentrated lateral load and so on. Some of these failure modes are elaborated upon in Chapter 18 - Analysis and Design of Ship Structure and 21 - Composites.

In general sandwiches are more expensive to fabricate than an equivalent structure in steel. Typically they are used in weight-sensitive vessels such as high-speed ferries and high performance sailing and motor yachts.

Some examples of recently developed sandwich structures will now be described.

Example lO-Trailer ramp. In Figure 17.1 the use of extruded aluminum sections for a deck was illustrated. Fundamentally this is a sandwich structure. In Figure 17.10 the incorporation of such a deck in the ramp of a Ro-Ro vessel is shown.

Example ii-Laser welding. Laser welding allows welding through the plate thickness to a second plate underneath. This enables welding of structures that hitherto could not be welded (see reference 22), and this makes the construction of all-metal sandwiches possible as shown in Figure 17.11 for steel and in Figure 17.12 for aluminum. Even bimetallic sandwiches are proposed with one steel skin and the other aluminum.

In order to connect adjacent panels special edge provisions must be provided (Figure 17.12). These provisions generally do not connect the core structures of the two panels. Thus the cores does do not contribute to the transmission of in-plane loads. Lateral shear loads can be transmitted only by the contact between core and edge stiffener. At the moment this limits the application of this type of sandwich structure to local, laterally loaded structures that do not participate in overall strength. Examples are staircases, watertight and non-watertight division bulkheads, landing platforms, tweendecks and similar. The use of aluminum sandwich panels in a modern large sailing yacht is illustrated in Figure 17.13.

Advantages in addition to the low weight are the small construction height, smooth exterior thanks to the laser welding, reduction of noise and vibration and possibly better fire protection characteristics.

Example i2-Bonding. Recently a new product appeared on the market where steel skin plates are bonded by a solid elastomer (23,24). The latter is injected after the skin plates are in position. The system is meant to replace traditionally stiffened steel plates.

The application shown in Figure 17.14 shows the span between two web frames or similar. A traditional steel structure would require 3 or 4 stiffeners, which now can be omit-

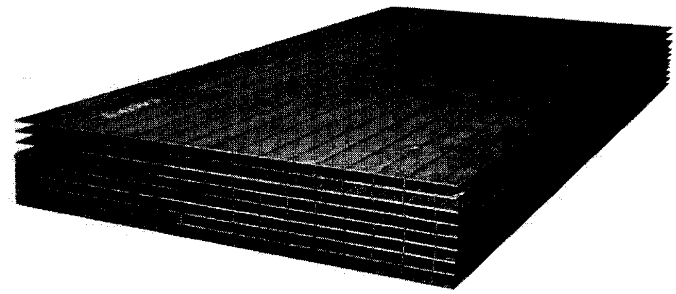


Figure 17.11 Stack of 40 mm Thick Steel Sandwich Panels

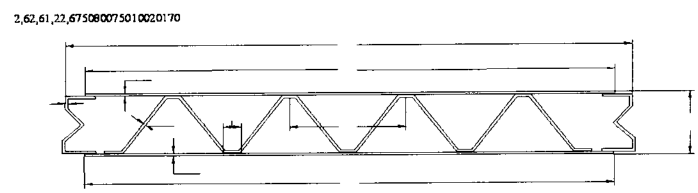


Figure 17.12 Cross Section of Aluminum Sandwich Panel with End Connectors

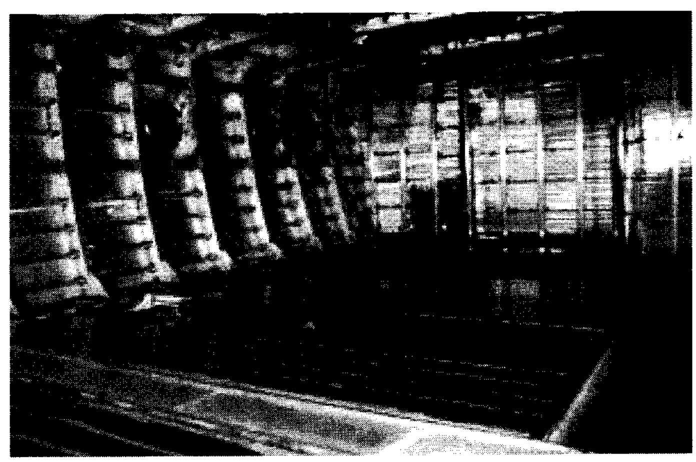


Figure 17.13 Aluminum Sandwich Panels Used for Decks and Bulkheads in a Sailing Megayacht

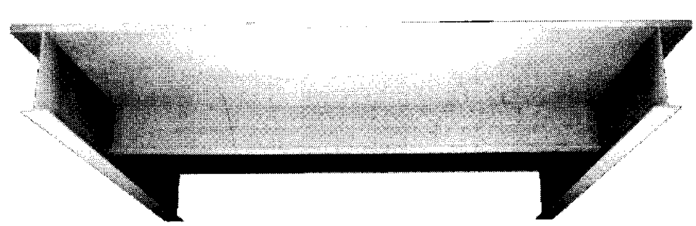


Figure 17.14 Support for Sandwich Panel

ted. The number of structural components and the amount of welding thus is minimized.

An additional advantage of the system is the fact that the core material is injected after the skin plates are installed. It means that the core consists of one continuous material. The core material has a better shear strength than several more traditional core materials. Together this means that the sandwich plate is more suitable to transmit shear forces than some other sandwich structures. The number of fatigue and corrosion-prone details is significantly reduced which makes maintenance easier. Added advantages may be better damping characteristics for noise and vibration and a good impact resistance. For repair of existing structures the fact that the system can be retrofitted using the existing stiffened plate as one of the skins is an important advantage for certain applications. Figure 17.15 shows the application in the repair of an existing Ro-Ro ferry deck. The mass density of the solid core must be considered in design and, in the case of repair where weight is added, the hydrodynamic stability of the ship should be checked.

As with all structural laminates, tension forces across the laminate should be avoided unless direct design calculations show otherwise. Connectors like epoxy embedded anchors can be used to transfer small tensile forces directly into the core to engage the entire sandwich plate without delamination.

Note that the term *sandwich* generally is applied to panels consisting of two skins with an intermediate core, together having a limited thickness and generally supplied complete by an independent fabricator. Structurally the same principles apply to some items normally fabricated by the shipyard. A good example is the rudder. Here the *core* consists of rather narrow steel strips. Welding is from the outside using slots and backing strips because of inaccessibility of the rudder for the welder (Figure 17.16 from reference 25).

A double bottom, a double shell or even a complete ship (over its full height) may be considered as a sandwich with material at its extreme fibers arranged so that accommodation of bending is maximized. Shear forces will then be transmitted via plates perpendicular to the extreme fibers. But normally such large structures will not be called sandwiches.

17.9.5 Membranes

Earlier it was mentioned that distributed transverse loads on plates may also be carried by in-plane stresses if the deflections of the plate are large compared to its thickness or when a large out-of-plane form of the plate has been built in.

Example 13-Sails. Sails are a good example of the use of membrane strength. Most people intuitively know the way in which these transmit the wind forces to the ship. Figure

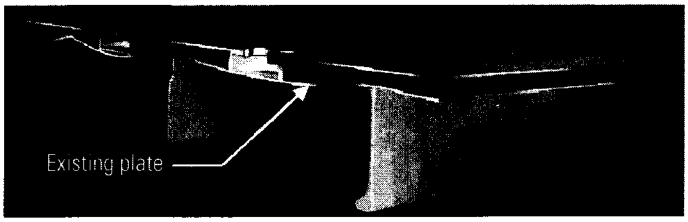


Figure 17.15 Structural Repair Using Elastomer Injected in Place

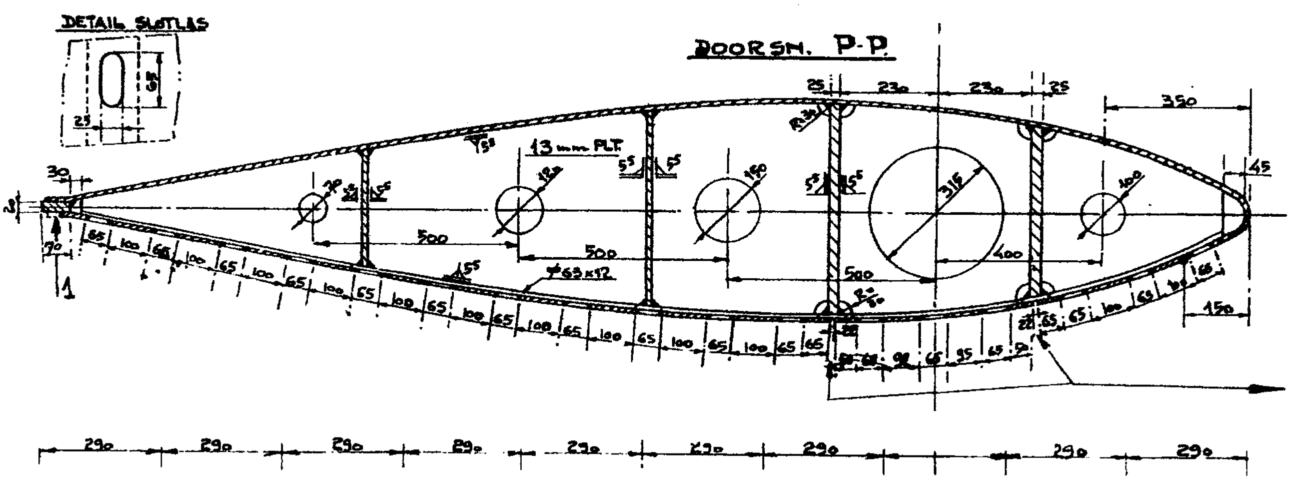


Figure 17.16 Cross Section through a Rudder

17.17 shows the transverse and longitudinal sails of the clipper *Stad Amsterdam* recently built in the Netherlands. The wind pressure is transmitted to either the edge ropes of the sail or immediately to the spars or mast by membrane stresses that exercise a distributed transverse load to those ropes or spars. The transverse load to the edge ropes will result in only tensile forces in a way similar to that in which lateral pressures are translated into membrane forces for the sail.

The in-plane force components that are inescapably concomitant to membrane forces then will be transmitted by the edge ropes (in tension only) and the spars (in compression and/or bending) back to the other side of the system. The total system of sail, edge ropes and spars transmits only the total wind force to the vessel. But within the system some very large forces may be present in components.

From this example it is clear that the use of the membrane principle requires that at the edges of the plate a structure must be provided to accommodate the in-plane component of the membrane stresses. An exception exists where loads are applied inside or outside a closed near-circle. In that case the membrane stresses may be in equilibrium within themselves.

Example 14-Membrane shell. Large tankers for transport of fresh water and similar non-polluting liquids were considered in the mid-90s. They would be built from flexible reinforced plastic sheets with an appropriate cross section (attained automatically) to guarantee membrane stresses only as shown in Figure 17.18 from reference 26. The idea does not seem to have been pursued since then.

The principle of accommodating lateral loads in membrane stresses is shown in Figure 17.19. A distributed pressure can well be accommodated by a smoothly curved plate (or membrane like a sail). No bending moments are necessary but there is a direct relation between the pressure applied and the local deformation of the plate (sail or rope, etc.). The consequence is that concentrated loads can be accepted only in this way if there is a concentrated deformation of the plate, a knuckle (as a result of the load or built in from the start). If the point of application of the load is not always the same, changing deformations and hence fatigue may be the result (unless very flexible material is used such as in sails). Use of membrane stresses to support lateralloads, therefore, is limited to some rather special structures and to situations where the load is accidental. Implicitly it sometimes is used to allow higher stresses than otherwise would be the case such as for the plate thickness of shell plating. In the case of watertight bulkheads development of a permanent deformation after accidental loading (flooding of a compartment) is accepted.

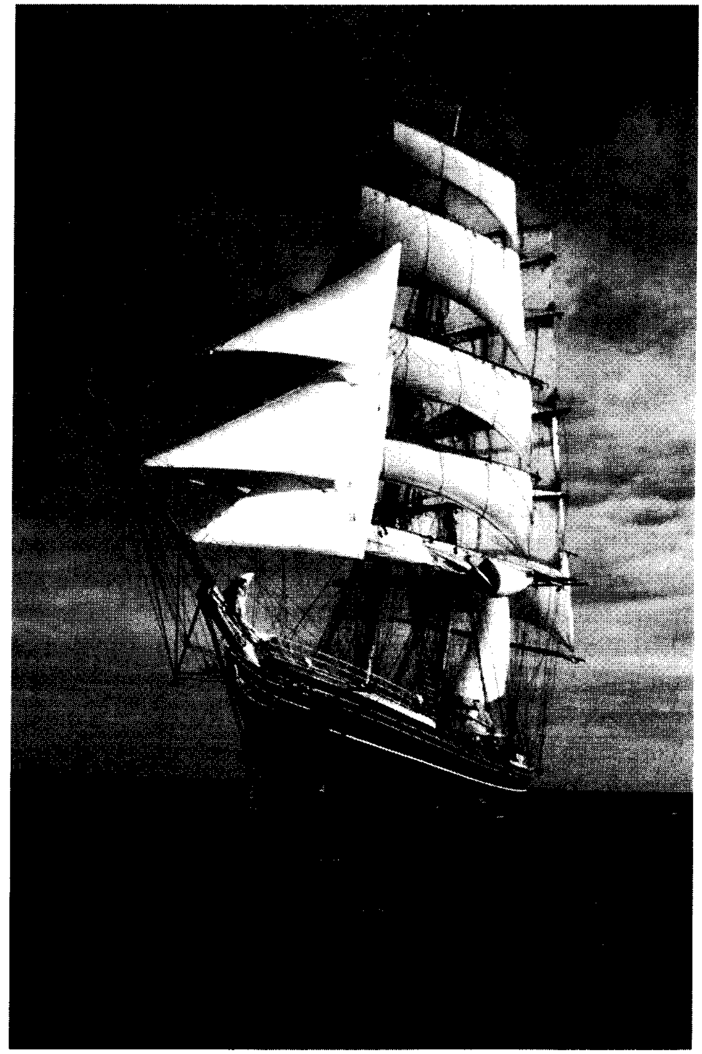


Figure 17.17 *Stad Amsterdam* Showing Sails Experiencing Membrane Strength

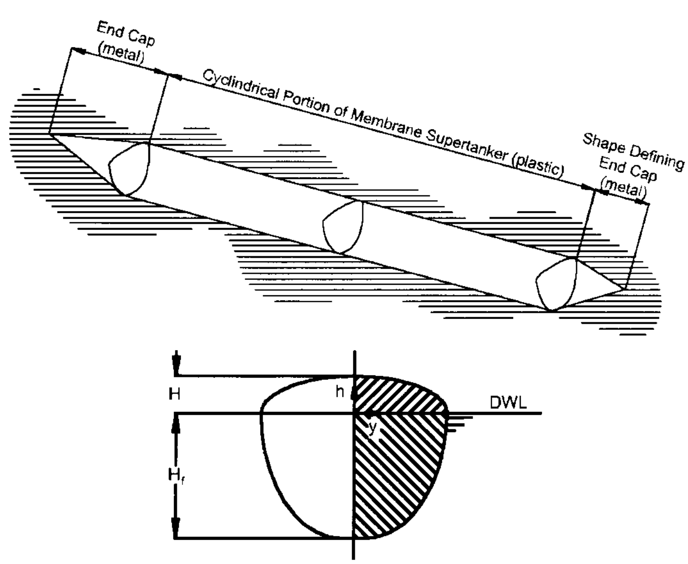


Figure 17.18 Flexible Membrane Shell Tanker

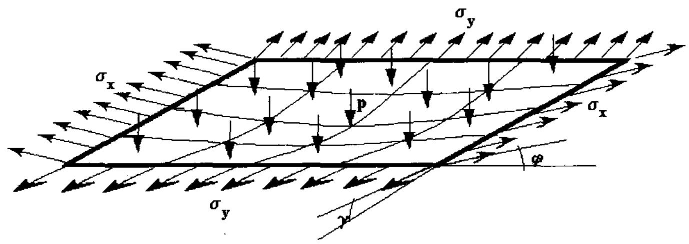


Figure 17.19 Principle of Membrane Stresses to Absorb Lateral Load

17.9.6 Transversely Loaded Beams Including End Supports

Transversely loaded beams are doubtless the most generally used components in any ship apart from the plating itself. Their main function is to transmit a lateral load from the point of application to the point where those beams are supported, mostly at one or both ends of the beam. The applied force can either be distributed, quasi-distributed or concentrated. Distributed loads are typically those exerted by water pressure via the plating onto the stiffeners. A quasi-distributed load consists of a series of concentrated loads coming close to a continuous distribution, such as the loads transferred by deck longitudinals into a deck transverse web frame. An example of a concentrated load is the load introduced from a rigging tie via a pad-eye into a stiffener. The load exerted on the beam is transmitted to its supports (generally at the beam ends) by means of bending and simultaneously by shear. These two methods of load transmission may be considered as two different (albeit inseparable) load paths. Following the principle described in section 17.7.5 the two methods share the total load in ratio to their stiffness between the point of application of the load and the support.

A detailed description of the distribution between bending and shear is given in reference 5. In general in may be stated that in long, not very high beams, such as stiffeners, bending is the dominant transmission mode. In shorter, high beams, such as web frames, shear transmission soon becomes dominant.

From the basic formulas of beam theory, such as in reference 17, it follows that in case the reaction forces at the beam-ends remain the same, the shear force distribution in the beam depends only on the distribution of the applied loads. The shape of the bending moment distribution in turn depends only on the distribution of the shear force, hence the load distribution. However, the complete bending moment line can be shifted up or down by a constant value depending on the end conditions of the beam (assuming that the end conditions do not change the vertical reaction forces as, for instance, in the case of a symmetric load). Whether the beam is free, fixed, simply supported or spring-supported on one or two ends, the bending moment distribution simply shifts up or down. This characteristic makes it possible to adapt the shape and dimensions of the beam to the requirements from the end support conditions. Those end conditions in turn may also be adapted by the designer. He may design the structure such that the end is simply supported, fully clamped or is characterized by a flexible support.

Example i5-impact of end conditions of a beam. A beam with a constant load per unit length is supported at its ends in two ways: clamped and simply supported. The shear force distribution is identical, but the bending moment line of the clamped beam is identical in shape but shifted upwards by an amount of *qP/12.* The maximum bending moment changes from *qP/8* to *qP/12.* More important is the location of the maximum bending moment, which changes from mid-span to the end of the beam. The maximum load at mid-span now is *qP124,* being the difference between *qP/8* and *qP/12.* The point ofthe maximum shear force remains the same, that is, at the end of the beam; at mid-span the shear force equals zero.

As already stated, the beam design may be adapted to the distribution and bending moment. In areas of high shear load the total web sectional area must be maximized, meaning that manholes and cutouts should be minimized. Such openings preferably must be located where the shear load is minimal. Where the bending moment is large, the distance between the extreme fibers (effective plate and flange or faceplate area) should be maximized and openings such as cutouts for crossing stiffeners in those areas should be minimized.

Example i6-Bottom transverse of a large tanker. The cross section over the central tank of a large tanker is shown in Figure 17.20 from reference 5. The transverse web frame may be considered as a beam loaded by a series of concentrated loads introduced by the longitudinal stiffeners. As stated earlier, for the gross behavior of the beam such series of point loads may be considered as an equally distributed load as shown.

The load is transmitted to the hull girder partly via the longitudinal bulkheads, partly via the center girder. The distribution over these two supporting members depends on the relative stiffness between the center girder and the longitudinal bulkheads. In this representation the bulkheads are considered infinitely stiff, whereas all the difference in stiffness between the center girder and the longitudinal bulkheads is combined in considering the center girder to be supported by a spring with spring stiffness *k.* With *k* equal to zero the center girder does not support the transverse at all; with k infinitely large the center girder and the longitudinal bulkheads participate in the same amount. This is reflected in the distribution of the shear force as indicated.

Note that the distribution of the shear force in the individual sections of the transverse web frame depends only on the end conditions of the beam.

The shape of the transverse web frame is adapted so that the shear area, the web sectional area, is maximized where the shear force is at its maximum. This is done by increasing the height of the web plate. Note also that manholes in the web may be provided near the center girder in case k is small. When k is large the shear force near the center girder is appreciable and such manholes should preferably be located halfway between the longitudinal bulkhead and center girder. At the same time the increased height of the transverse web frame makes the section modulus of the beam larger at the point where the bending moment is at its maximum. But in the given example this probably is less important, and shear will be dictating.

Example 17-End conditions of a deck transverse. The second example concerns a traditional transverse deck beam of a tweendeck of a general cargo ship (Figure 17.21). The shell and the hatch side coarning support this beam. The beam end at the hatch coaming must be considered simply supported

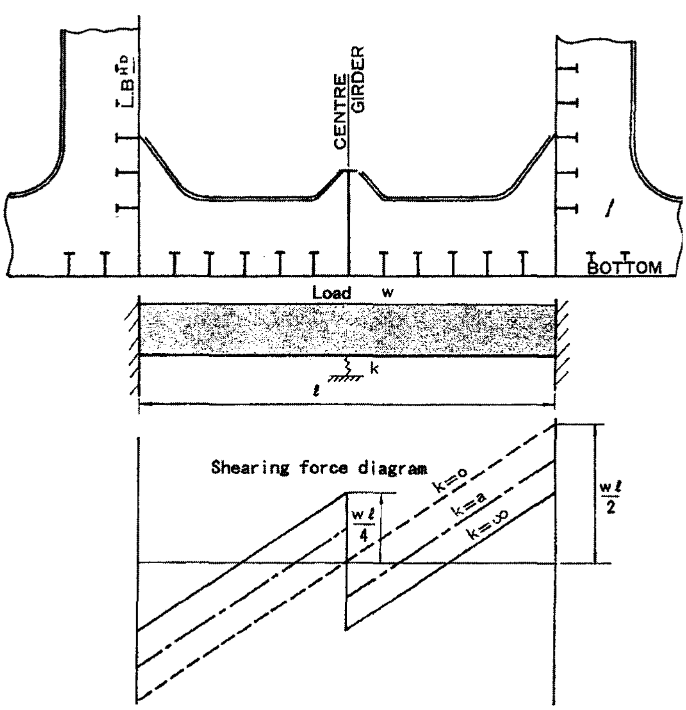


Figure 17.20 Tanker Wing Tank Transverse Web Connection to Center Vertical Keel

because the hatch coaming, possessing an open cross section, cannot provide the bending moment needed for a clamped end condition. At the shell end of the beam a condition exists between simply supported and clamped. This is because any moment at the end of the beam would have to be transferred to the side shell stiffener. The end of that side shell frame would rotate under influence of the moment and thus not be similar to a clamped end condition.

Note that in this example the designer can change the end conditions if, for whatever reason, it is desired to do so. A hatch coarning with a closed cross section could accommodate in torsion a bending moment coming from the deck beam. The end condition would then come close to a clamped or fully fixed situation. Similarly a deep web on the side shell instead of a side shell stiffener of normal dimensions could accommodate a much larger bending moment being transferred from the deck beam. Again the end condition in this way could come close to being fully clamped.

The previous example clearly shows that bending moments (or any other load forms) must be transferred from one structural component onto another one. A bending moment must be transferred from the deck beam into the side shell frame. If the two elements are of similar dimensions it is possible to transfer such end moments directly.

The connection between the two components, the deck beam and the side shell frame, is shown in Figure 17.22. The webs of the two profiles are attached back to back with the flanges pointing in opposite directions. The bending stresses in the deck beam are to a significant amount concentrated in the flange of the profile. Similarly the bending stresses ofthe side shell stiffener are concentrated in the flange of that stiffener. All those stresses must be transferred from one flange to the other by means of the weld connecting the two profiles. Without going into a detailed consideration of how this is performed, it will be obvious that the connecting weld will

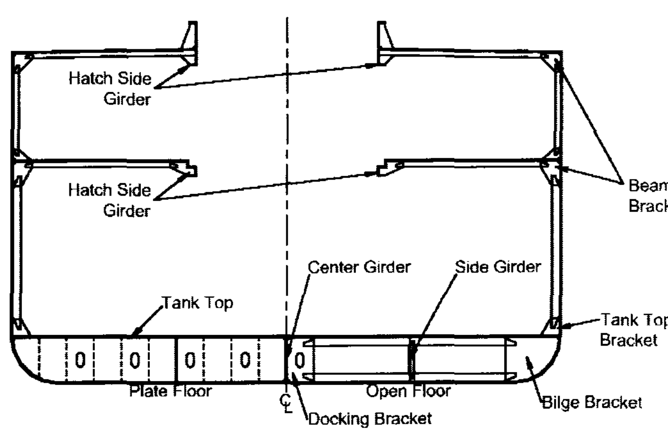


Figure 17.21 Traditional Transversely Framed Cargo Ship Midship Section

experience very high stresses or, in other words, this will result in a very high stress concentration.

When the load is more or less static, such high stress concentration may be acceptable considering that the highly stressed area is limited in size and that that part will yield to some extent (thus showing a non-linear stress-strain relation) and hence the stress will be redistributed. In general, however, such stresses will fluctuate in magnitude and the risk of fatigue will be high. Therefore, the design shown in Figure 17.22 is generally not acceptable. In particular it will be difficult to see an effective way to accommodate the bending moment over the diagonal cross section A-A.

A better design is to use a bracket in order to transfer the bending moment from the deck beam to the side shell stiffener (Figure 17.23). The bracket's role is to assist in the transfer of the bending moment. Now the diagonal cross section is quite effective in accommodating the bending moment. The height of the cross section is more than both that of the deck beam and that of the side shell stiffener. Also a flange can be provided at the lower edge of the bracket as described hereafter.

Finally the bracket already starts to transfer the bending moment at a point of the beam more inward; in other words the unsupported span of the beam is decreased. It is helpful to illustrate the effect of the bracket by considering the force transmission by stress lines as mentioned in section 17.9.2. Immediately it is clear that a careful design of the connection between bracket flange and flange of the beam is needed in case of large bending moments. Discontinuity in the material may lead to high local stresses and consequently the risk of fatigue. On the other hand it may be that the location of the beginning of the bracket is such that the bending moment at that point of the beam is not high. As a consequence it is possible that no flange is needed. Also the' height of the bracket over its A-A diagonal cross settion again may be sufficient to eliminate the need for a flange. But even in that situation a flange will often be provided to prevent buckling of the otherwise unstiffened bracket edge loaded in compression. In this situation it is quite acceptable that the flange is not continuous with the flanges of the deck beam and the side shell stiffener. The classification societies allow the use of flangeless brackets but require the bracket to be thicker than the same size bracket with a flange.

Note that the flange of a bracket offers a clear example of how seemingly similar structural components may play quite different roles in accommodating loads and stresses. It also illustrates the different failure mechanisms that the structure may experience. All those differences make details acceptable in one situation, which are completely unacceptable in other situations.

Sometimes consideration of space (or the cost involved

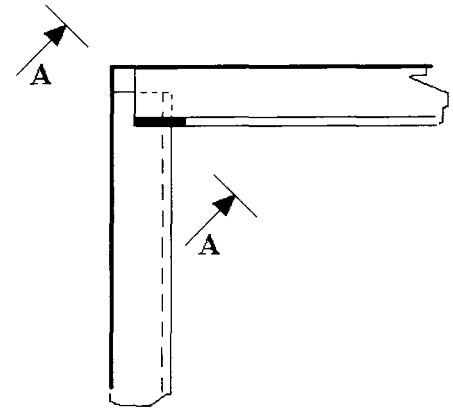


Figure 17.22 Simple Bracketless Beam/Frame Connection

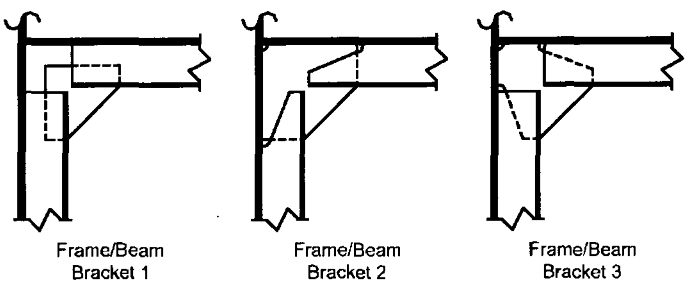


Figure 17.23 Beam/Frame Bracket

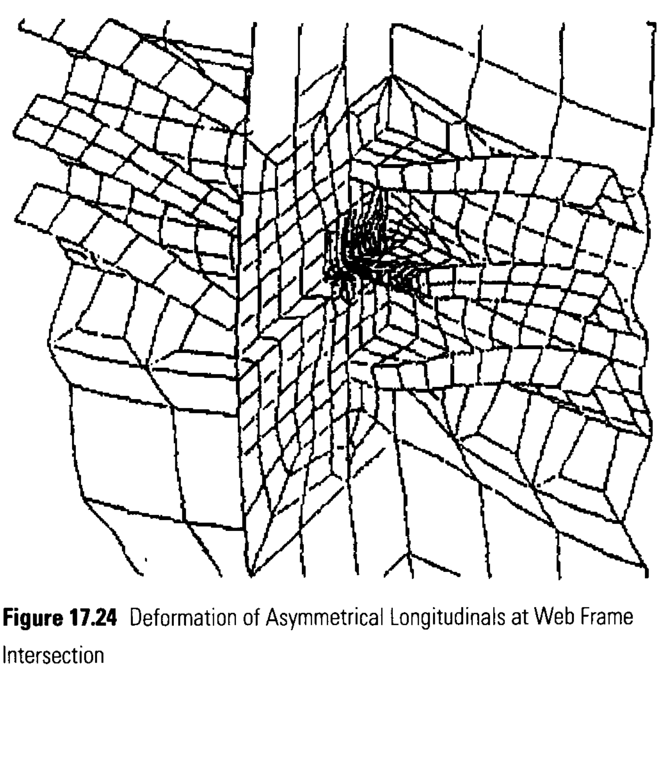


Figure 17.24 Deformation of Asymmetrical Longitudinals at Web Frame Intersection

in use of a large number of components) would preferably not use bracketed connections.

Example 18-Bracketless end connection. In a car ferry or car transport ship space is at a premium in order to allow the maximum number of cars with a limited building height. The connection between deck and side shell webs may be designed without brackets. A careful design and analysis of the connection is necessary to prevent the risk of overloading and crack initiation. In this situation additional stiffeners may have to be used to make an effective transmission of the bending moment possible.

Many beams do not have a symmetrical cross section. In that case the shear center is not positioned in the same vertical plane as the attachment of the beam to its related plating. Consequently any load on the beam will exert a torsional moment, which in the beam theory as normally used, is not taken into account. This torsion moment may cause large stresses in addition to the normal bending stresses. If fluctuating this may cause fatigue.

Example 19–Torsion from asymmetric stiffener. Longitudinal side shell stiffeners of tankers showed many cracks in the 1980s at their connections to web frames. Figure 17.24 from reference 27 shows the deformations as calculated in a finite element calculation. The additional torsion stresses caused by the eccentric load on the stiffener, due to its asymmetry, are obvious. They are caused by the water pressure exerted on the vessel's side shell. The fluctuating character of these deformations and stresses in combination with minimization of the scantlings and the use of high-strength steels are the main cause of the fatigue cracks.

Asymmetrical profiles may not only have problems at their end connections. Because of the eccentric loading the risk of lateral-torsional buckling, the so-called *tripping*, is also increased. This means that *tripping brackets* will be sooner required than is the case for symmetrical profiles. This may be even more so when the load is obviously eccentric such as when a concentrated load is on a deck on one side of the stiffener.

Figure 17.25 shows typical arrangement for the intersection of a stiffener with a web frame. For the asymmetric profile a non or single connection chock is needed.

The symmetric section used two chocks in the past, but today the trend is toward the slot connection with no chocks. It now is possible to slide the sections through the accurately cut openings in the web plate (see Tee 6 in the figure). In the past this was not possible. What is true for stiffeners is also true for brackets.

Traditionally brackets were attached overlapping the stiffeners as in Figure 17.23. This makes for easy fit-up in fabrication (and thus was another argument in favor of nonsymmetric profiles). However, when the bracket must transfer a bending moment, as described earlier in this section, the eccentricity of the bracket plate relative to the stiffener, causes a secondary bending moment perpendicular to the plane of the bracket and the stiffener. Again this causes additional stresses and the risk of fatigue. In optimized structures, therefore, brackets are preferred that are symmetrical to the (then generally also symmetrical) stiffeners.

Note that the arguments for symmetrical stiffeners and brackets apply even more to aluminum than to steel structures because this material is more fatigue-prone. Also aluminum generally is used for high performance vessels where weight is at a premium and the structure is generally more optimized. This shows how the material selection impacts on details of the structural design.

17.9.7 Orthogonally Stiffened Plate Panels

17.9.7.1 Laterally loaded orthogonally stiffened plate panels

The previous section dealt with the ubiquitous use of transversely loaded beams and their end connections. Most of the examples showed situations where the vertical load at the end of the beam is transferred into a structural member that itself has a direction more or less parallel to the load exerted on the beam. Often in ship structures a different situation exists. The beams transfer their load into members lying in the same structural plane, which in itself is also perpendicular to the loads. These members in turn may transfer their loads to still other members in the same plane being again perpendicular to the previous members (and hence parallel to the original first members).

Example 20-0rthogonal stiffening. The work deck of a semi-submersible support vessel is designed for a distributed load of, say, 10 tons/m^2. The load will be transmitted by the deck plating to the longitudinals (see Section 17.9.1). The longitudinals transmit the load to the transverse deck webs in the way described in the previous section. In a similar way these webs in their turn transmit the load to the longitudinal bulkheads. They again transmit the loads to transverse bulkheads, which finally transmit the load to the vertical members of the columns connecting the upp~~pontoon of the semi-submersible to its lower pontoons. In the lower pontoons in a similar way the load is distributed via longitudinal and transverse bulkheads to the webs, bottom stiffeners and finally bottom plating to equalize with the water pressure on the bottom.

In example 20 a repeated transfer of the load to elements of an orthogonal stiffening system is described. Each subsequent elemental system level has a larger distance and unsupported span, but also a larger moment of inertia. It is obvious that the system with some five types of elements as described in the example is quite complicated. Often the number of elements is not more than 3, that is, longitudinal stiffeners, transverse webs and longitudinal girders and other edge supporting structure (assuming that the longitudinal shell plating is not considered to be an element of this system) as shown in Figure 17.26 from reference 2. The designer can select the number of element types, the unsupported span and the distance between similar elements'more or less at will. Apart from general layout considerations, the choice is mostly dictated by minimization of either fabrication cost or structural weight or a compromise for both. Most normal ships optimization studies, and past experience, show that stiffener distances of 0.5 to 1.0 meter offer practical values (the larger figures for larger ships), web distances (and thus unsupported spans for the stiffeners) realistically are 2.5 to 5.0 meters. Web spans (and thus distances between longitudinal bulkheads) often are around 10 to 12 meters. Note that gradually the increase ofthe unsupported span becomes smaller. This means that the relative importance of bending compared to shear is more for the smaller elements than for the larger. For the bulkheads shear often is dominant. In aluminum high-speed vessels those values for the stiffener spacings may be smaller.

A characteristic for an orthogonally stiffened panel is that most members extend over more than one supporting member. Figure 17.27 from reference 2 shows a deck longitudinal supported by several web frames. When the longitudinal is loaded over its full length by a constant deck load (here represented by a load per meter length) considerations of symmetry indicate that the longitudinal, at each webframe, experiences a bending moment, but does not experience a rotation under influence of the load. The longitudinal at that point may be considered to be clamped. Contrary to the situation as described in the previous subsection this bending moment now is counteracted by the bending moment in the adjacent part of the same longitudinal. This means that no bending moment is transferred into the supporting member, the web frame, and consequently no brackets or similar connections are needed to transfer the bending moment. The

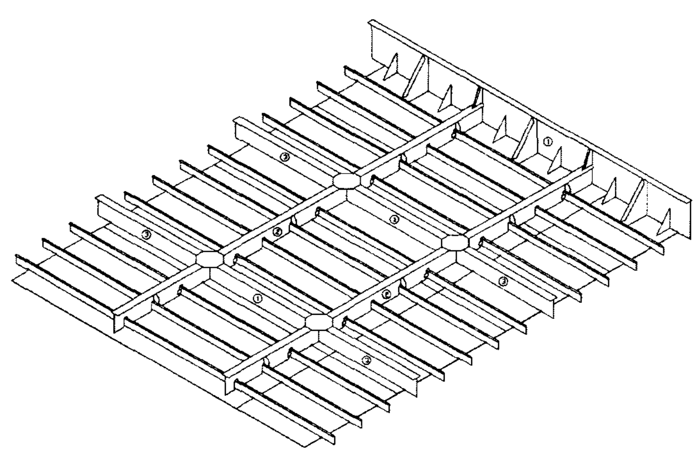


Figure 17.26 Orthogonally Stiffened Deck Panel

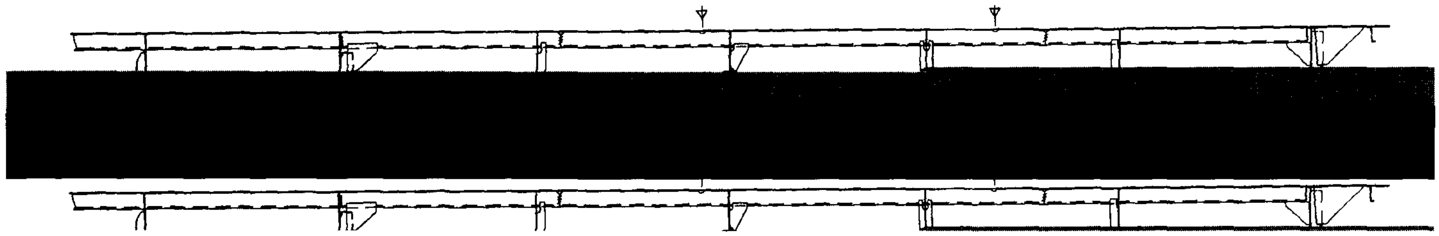


Figure 17.27 Longitudinals Extending Over Many Webframes

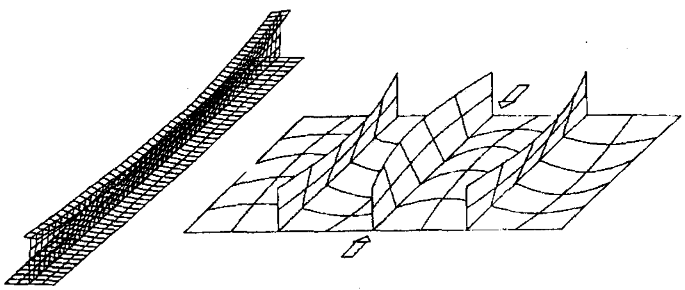


Figure 17.28 Torsionally Buckled Stiffeners

shear force from the longitudinal, however, must be transferred into the web frame.

A typical way to do this is illustrated in Figure 17.25 where chocks connect the longitudinal to the web and transfer the shear force. Sometimes an additional stiffener on top of the longitudinal is also provided to transfer this shear force. Note that this shear connection must transfer the shear force coming from the longitudinal at both sides ofthe supporting web frame. The force exerted on the web thus is double what it would have been if the longitudinal ended atthe webframe. In many situations the load on the stitteners is not continuous as was assumed until now. For instance on the deck of a work vessel it is quite possible that a load is applied only on one side of the supporting member. In such a situation the assumption of symmetry around the support is no longer valid.

The longitudinal between its supports cannot be considered as clamped. It is not simply supported either, but flexibly supported. The maximum bending moment is not *1/12qf2* as for the clamped situation or *1/8qf2* as for the simply supported condition, but something in between, say in the order of magnitude of *I/IOqf2.* The longitudinal at its supports will experience a rotation under the load. In general this cannot be prevented by the supporting member because that does not possess the torsional rigidity to do so (unless specifically designed to prevent rotation). Sometimes this creates a problem in the supporting member, for instance when that member in itself would be fixed nearby. The rotation over a short distance then could create high local stresses. In particular when the deflection is fluctuating this can create fatigue problems.

17.9.7.2 In-plane compressive loading of orthogonally stiffened plate panels

Plate panels, including orthogonally stiffened panels, often are loaded in their plane. When such loading is tensile the stiffening members do not play any specific role. The cross sectional area of members parallel to the load adds to the cross section of the plate itself and thus reduces the maximum stress.

It is different, however, in case of in-plane compressive loads. For a given plate thickness the buckling strength of the plate panel depends in particular on the free plate length, that is, the distance between its stiffeners. As mentioned in Subsection 17.9.3 stiffeners in the direction of the applied load are the more effective but stiffeners perpendicular to that load are also possible (see the referenced books on engineering mechanics for more details). Generally it is assumed in plate buckling that the stiffeners will provide a simple support to the plate, that is, no displacement perpendicular to the plate is assumed, but rotation is possible. In special cases this may be avoided by using stiffeners with a closed cross section that can resist torsion, such as square tube.

It is obvious that the stiffeners more or less parallel to the load when in compression will be subjected to a buckling load. More than one buckling mode will be possible for stiffeners in this condition. But the most likely form of buckling will be *tripping,* that is, local torsion of the stiffener around its attachment to the plate (see Figure 17.28 from reference 28).

Such stiffener buckling is prevented by the orthogonally arranged support, such as webframes. In this case the web frame distance is decisive for the buckling strength of the stiffener. If that distance is too large and consequently the buckling strength of the stiffener insufficient, the use of intermediate *tripping brackets* will be necessary. Tripping brackets sometimes are replaced by tying in two adjacent stiffeners with one carling.

17.9.7.3 Grids

The orthogonally stiffened panel is characterized by a hierarchy of members with increasing span and cross sectional stiffness. Such system sometimes is also called a *grid.*

It would be better, however, to restrict this term for the not very common situations where loads can be transmitted into more than one direction because stiffeners or other members of similar stiffness run in different, often orthogonal, directions. The load path then consists of two parts. A good example is the double bottom of a bulk carrier as described in example 39 in section 17.10.4.3.

17.9.8 Longitudinally Loaded Beams and Trusses

By far the majority of all ship structures consists of stiffened plate panels loaded laterally or in-plane. In the former case the load is generally a distributed one acting on the plate, which transfers this load into the stiffeners as described in Subsection 17.9.7. But sometimes structural elements are line members. These practically always are loaded at their ends, mainly with compressive or tension loads in line with the element. Often this is combined with a secondary bending moment, and in that case also a transverse shear load. Beams that carry a lateral load over a major part of their length mostly form part of a larger structure. They are described in Subsection 17.9.6.

Generally the reason for using a beam-like longitudinally loaded structural element is that this is the most weight-efficient way to transmit a force, as mentioned in section 17.7.3. Added advantages may be found such as minimization of hydrodynamic resistance or keeping as qpen a view as possible. ~.

Example 21-Floating shear-legs. Figure 17.29 shows a heavy-lift floating shear-leg. Obviously the hoisting wires are elements in pure tension. Other elements, such as the A-frame, are compression members. The latter have a more substantial cross section. Not necessarily so in cross sectional area, but in moment of inertia. This is necessary to avoid buckling of such members. Note that the length ofthe tension members is adjustable in order to provide the desired lifting height and outreach. Also note that the arrangement is such that some, but probably relatively little, side load can be accommodated by the structure. Clearly it will be difficult to find a more weight optimized structural concept than the one shown.

Even in traditional ships many structural elements still exist that are longitudinally loaded. Typical examples are

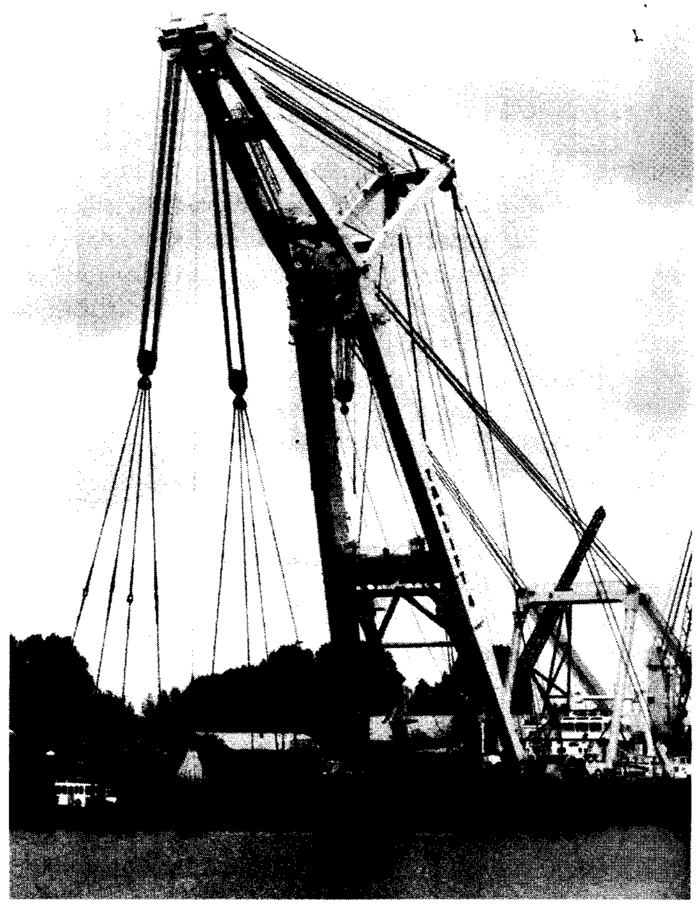


Figure 17.29 Heavy-lift Floating Sheer-leg

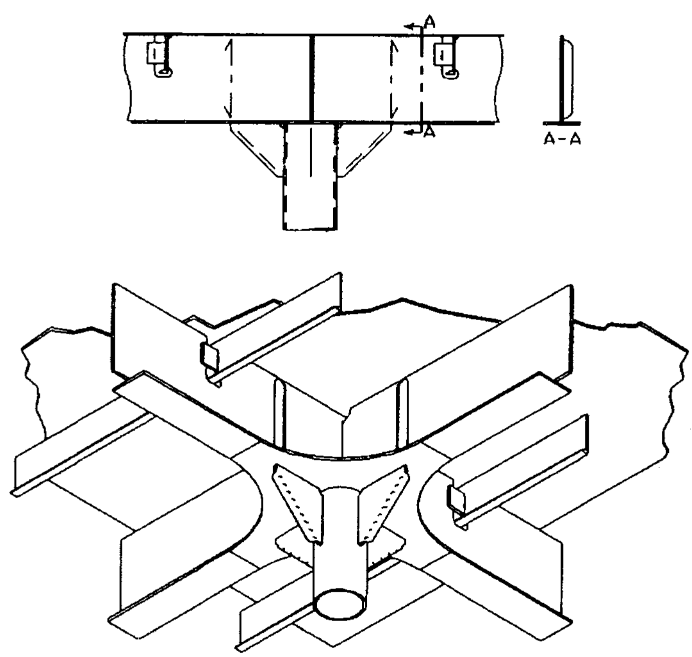


Figure 17.30 Typical Pillar-to-Deck Connection

masts, davits, supports for bridge deck extensions, and, in particular, pillars in the hull and the superstructure. Generally the pillars serve to transmit the weight of ship structure, outfitting items and cargo to a lower part of the ship structure and finally to the bottom structure (where it will equalize with the water pressure). When such members are loaded in tension, only their cross sectional area is important. Loaded in compression, however, they may buckle as a column. This means that the moment of inertia, the column length and its end conditions are important to obtain an adequate structure. For that reason pillars are often constructed from tubular members being the more effective cross section. Unfortunately, round tubular members do not fit well into the normal ship structure, which consists of orthogonal fla,t'plates and stiffeners. Continuity of material is difficult to attain. When loaded in compression the solution found generally uses either intermediate plates loaded in bending and/or brackets inserted in the column (Figure 17.30 from (2). Note that two opposite brackets preferably should be one continuous member in order to avoid rotation of the individual bracket into the tubular plating. This would create a hard point in that plating and might easily lead to cracking.

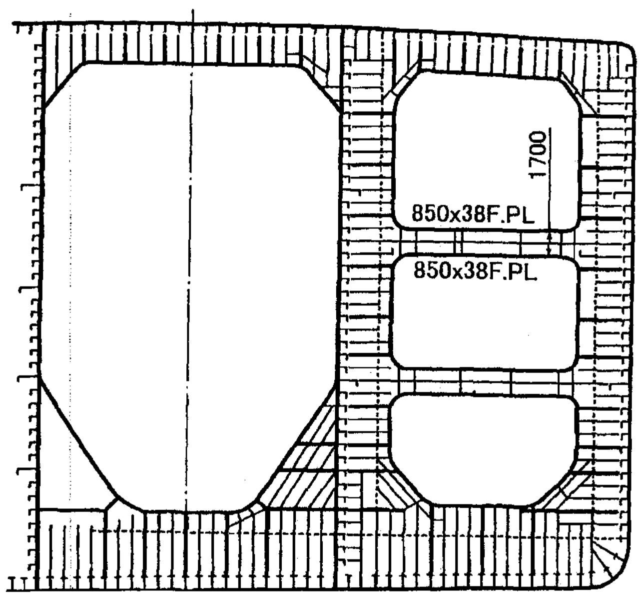


Figure 17.31 Midship Section of 480 000 TDWT Single-hull Tanker with Side Tank Crossties

Sometimes pillars are loaded in tension instead of compression, such as when a pillar must transmit a tension force for instance when located underneath the aft end of a winch. But other linear members also exist such as the connection tie between a tanker's side shell and its longitudinal bulkhead.

Example 22-A tanker cross section. Tankers, whether double- or single-hulled, often have cross tie beams connecting longitudinal bulkheads and shell structure in the side tanks (Figure 17.31 from reference 5).

They reduce the unsupported span of the webframes along the bulkheads/shell by transmitting some of the transverse load to the opposite side in the shortest way possible. Note that generally these line members are built up from plates and stiffeners rather than being tubular members.

Tension in pillars is also found when wave impact pushes the bow structure of a container vessel upward (5). But tension may also be the result of overall deformations.

Example 23-Tension pillars in a long superstructure. The superstructure of a passenger cruise liner must deflect with the

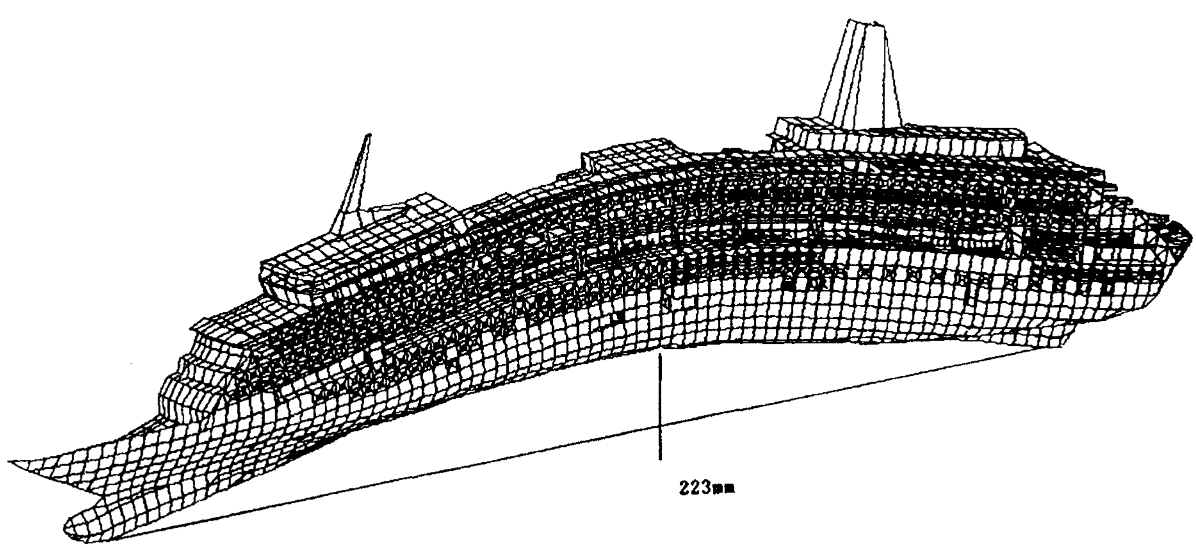


Figure 17.32 Longitudinal Bending of a Cruise Liner

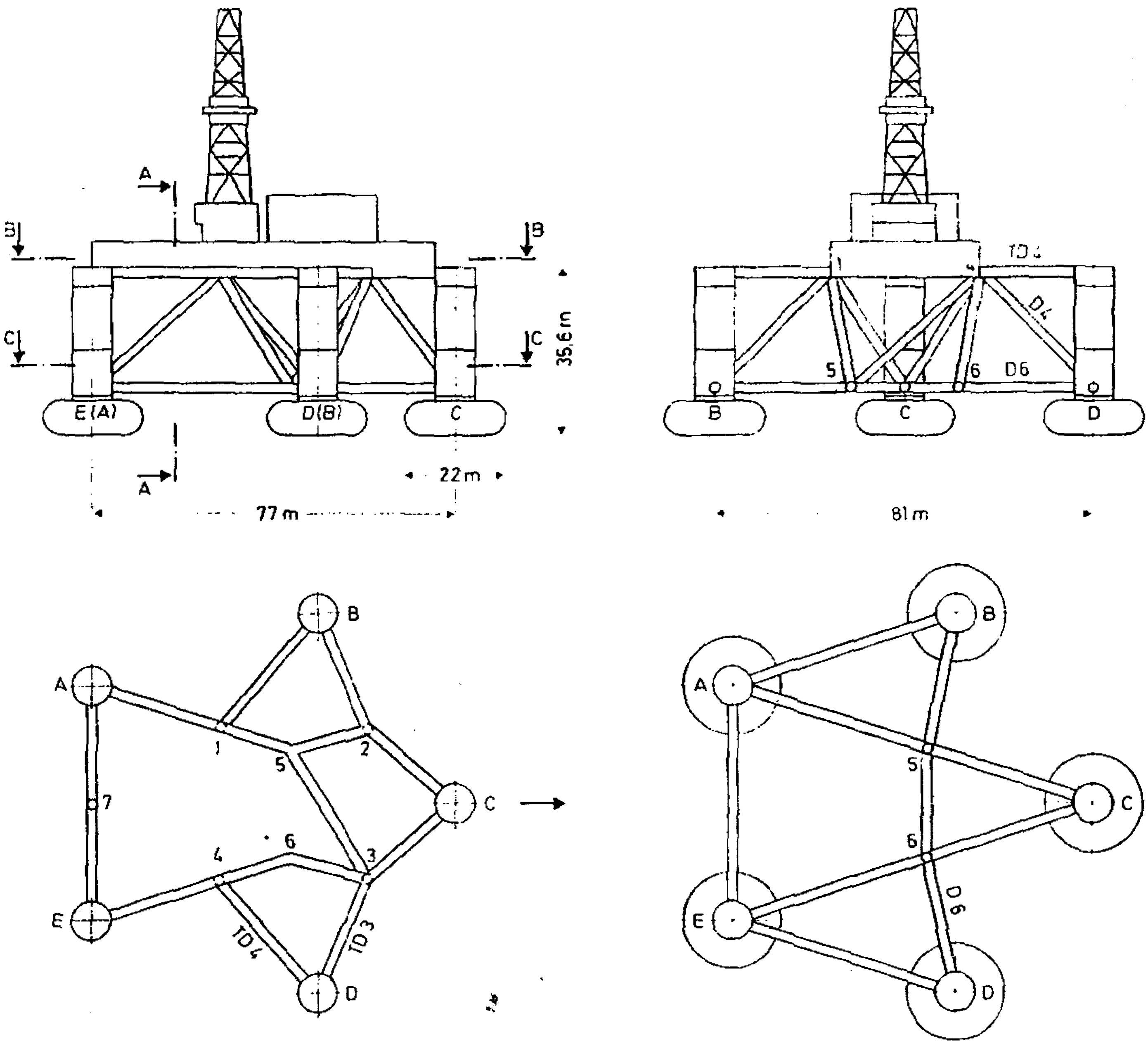


Figure 17.33 The Semi-submersible as a Space Frame

ship's hull when it is flexing under wave action. Figure 17.32 from reference 29 shows that the pillars in the forward and aft region of the superstructure will be loaded in tension in order to assure that the superstructure follows the hull deformation.

Use of a doubler plate in the design of the end support for a pillar loaded in tension, is not acceptable. Special designs must be used with continuous material such as brackets instead.

In novel ship type structures the use of longitudinally loaded members is far more common. For instance trusses or space frames are often used in the offshore industry. An early example of a semi-submersible drilling platform clearly shows the use of a space frame (Figure 17.33 from (30), but basically modem semi's as described in Chapter 45 also use the same structural principles, although less visible.

The legs of a jack-up platform (Figure 17.34) offer another example. Also many parts of offshore units such as crane booms, loading arms, personnel bridges, and drilling derricks, make use of trusses. Sometimes a truss is also used as a reinforcing and stiffening system in a hull instead of bulkheads (see for instance Figure 49.13 where this is done for a heavy-lift ship).

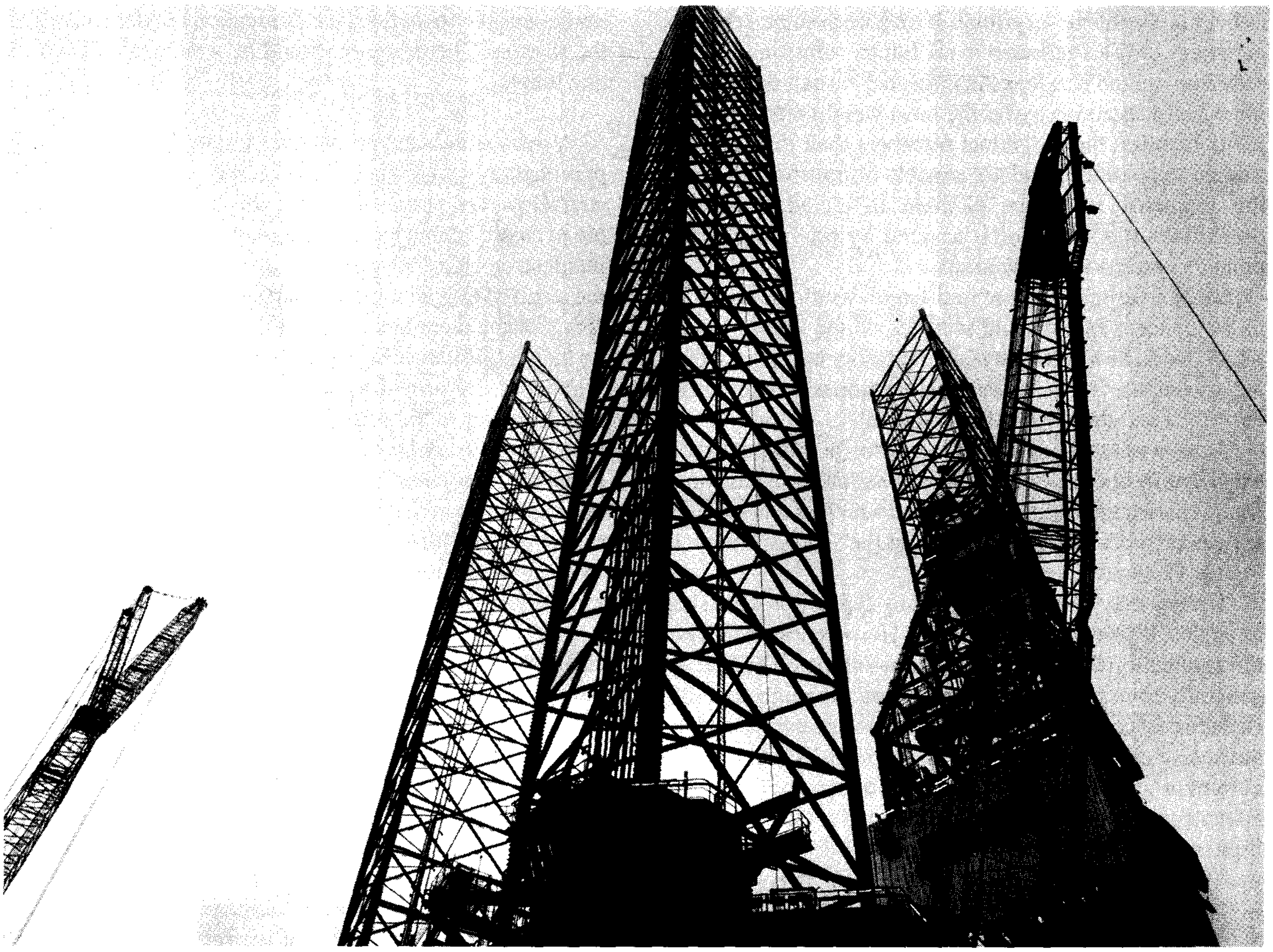


Figure 17.34 Legs of a Self-elevating Jack-up Platform

The main reason for using a truss is that it provides for a very weight-effective structure to transmit forces. The principle of a plane truss is illustrated in Figure 17.35. The truss can be thought of as one beam. A lateral load *P* is transmitted by the trusslbeam to the end supports. The shear force and bending moment distributions are as indicated. In a traditional beam this results in bending and shear stresses in the cross section as described in Subsection 17.7.3. The truss at the same location along length must accommodate the same shear force and the same bending moment. The latter is accommodated mainly by a compression force in the upper beam (in trusses generally called *upper chord)* and a tensile force of the same magnitude in the lower chord with the height of the truss as moment arm.

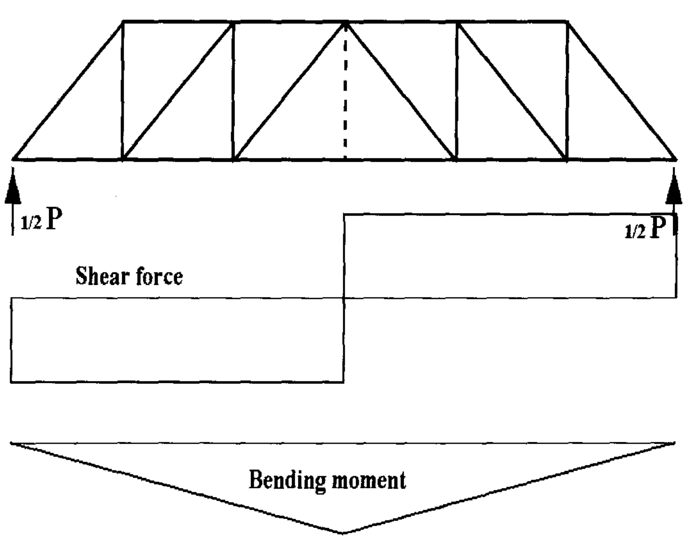


Figure 17.35 Principle of Plane Truss

The shear force is transmitted via the diagonal and vertical members, generally called *braces,* alternately with tension and compression forces. If the bending stiffness of the individual beams is very small it may be assumed that the members only experience axial forces (tension or compression) and no bending. As indicated earlier, this type of force transmission is by far the most weight effective. The joints between the individual members then may be considered to be pinned and not capable of transferring bending moments from one element to an adjacent one. Sometimes this behavior is assured by providing actual pinned connections at the joints.

Often a vertical brace at mid-length would be provided in the concept as indicated with the dotted line in Figure 17.35. Note, however, that such a member basically would not participate in any of the load transmission previously described and thus would be redundant.

A plane truss means that all members (or their centroidal axes) are in one plane and may be called 2-dimensional. Many trusses are 3-dimensional and are then called *space trusses* or *space frames.* The legs of the jack-up shown in Figure 17.34 are a clear example.

Trusses may be built up from any type of profiles such as angles, I-beams or square tubes. However, for underwater applications (jack-up legs, semi-submersible braces) generally round tubes are used because of weight and fabrication cost considerations. Round members have the added advantage of generating low hydrodynamic forces when in current or waves or wind resistance. To increase the weight advantage for some applications the trusses are designed in high-strength steel (yield 360 or 420 MPa in semi-submersibles) or very high strength steel (yield 510 or 690 MPa in jack-up legs).

As previously mentioned, ideally truss joints are pinned or may be considered as such, but in many situations reality is far from this. Bending of the members between the joints then must be taken into account. Such bending can· be caused by transverse loads on the members betwe~ the joints such as by the hydrodynamic forces acting on the legs of ajack-up. The effect of this type ofload is generally quite small compared to the effect of overall loading. But often a major reason for bending moments between the joints is the overall deformation of the space frame. This may cause a rotation between adjacent members at the joint. But when the joint is not really pinned the continuous members can accommodate such rotation only by secondary bending.

Example 24-Effect of eccentric joints. The importance of this can be seen from Figure 17.36 taken from reference 31. The stresses taking bending into account are much higher than when this is not done. Partly this can be the consequence of the conceptual design.

In the example the axis of chord, diagonal brace and transverse brace mayor may not intersect in the same point. Some set-off is beneficial for fabrication but detrimental to the stresses. The designer should be well aware of effects like these.

A truss allows an optimal use of material. Members are provided only when they are necessary for force transmission. However, at the same time this makes them vulnerable in case of damage. Damage may be caused by external incidents such as collision or a dropped object, or may be the result of fatigue initiation and subsequent crack growth. If any of the members in Figure 17.35 fails, the frame can no longer fulfill its load-carrying role, as the structure is not *redundant.* By providing additional members, such as diagonal braces in the other direction in Figure 17.35, some amount of *redundancy* can be provided. Damage of the upper or lower chord would still cause collapse of the truss and hence also in that concept it is not fully redundant. Note that in general plate structures are considered a lower risk in terms of redundancy because crack growth may take much more time before a critical crack length is reached.

Example 25-A non-redundant semisubmersible. The accommodation semi-submersible *Alexander Kielland* in 1978 developed a fatigue crack in one of its horizontal braces (Figure 17.33) that went undetected. In a storm the crack reached its critical length and the bracing member severed. The remaining structure had to accommodate the splitting force exerted on the floats and columns by means of bending in the remaining braces. Those could withstand that for only a short period and one complete column broke off. This meant loss of stability for the remaining structure. It toppled over with many lives lost. The accident meant to the industry a complete rethinking of the subject of redundancy. Classification societies and governmental regulatory bodies drew up requirements in this respect. Today most semi-submersibles possess upper platform and lower pontoons and columns built up as stiffened plate structures. Those major parts of the structure are closely integrated (Figure 17.37). The bracing system may consist of horizontal transverse tubes only. Redundancy in those designs is far less of a problem than for the older space frame semi-submersible designs.

The design of tubular joints is particularly important. Local stress concentrations are difficult to avoid. If fatigue cracking in semi-submersibles or jack-up legs exists, it is often caused by such stress concentrations at tubular joints. In particular when such types of vessel are used for production of hydrocarbons (see Chapter 43), with their inherent long exposure to sometimes very harsh environment at one location, fatigue may be dictating for the design of details.

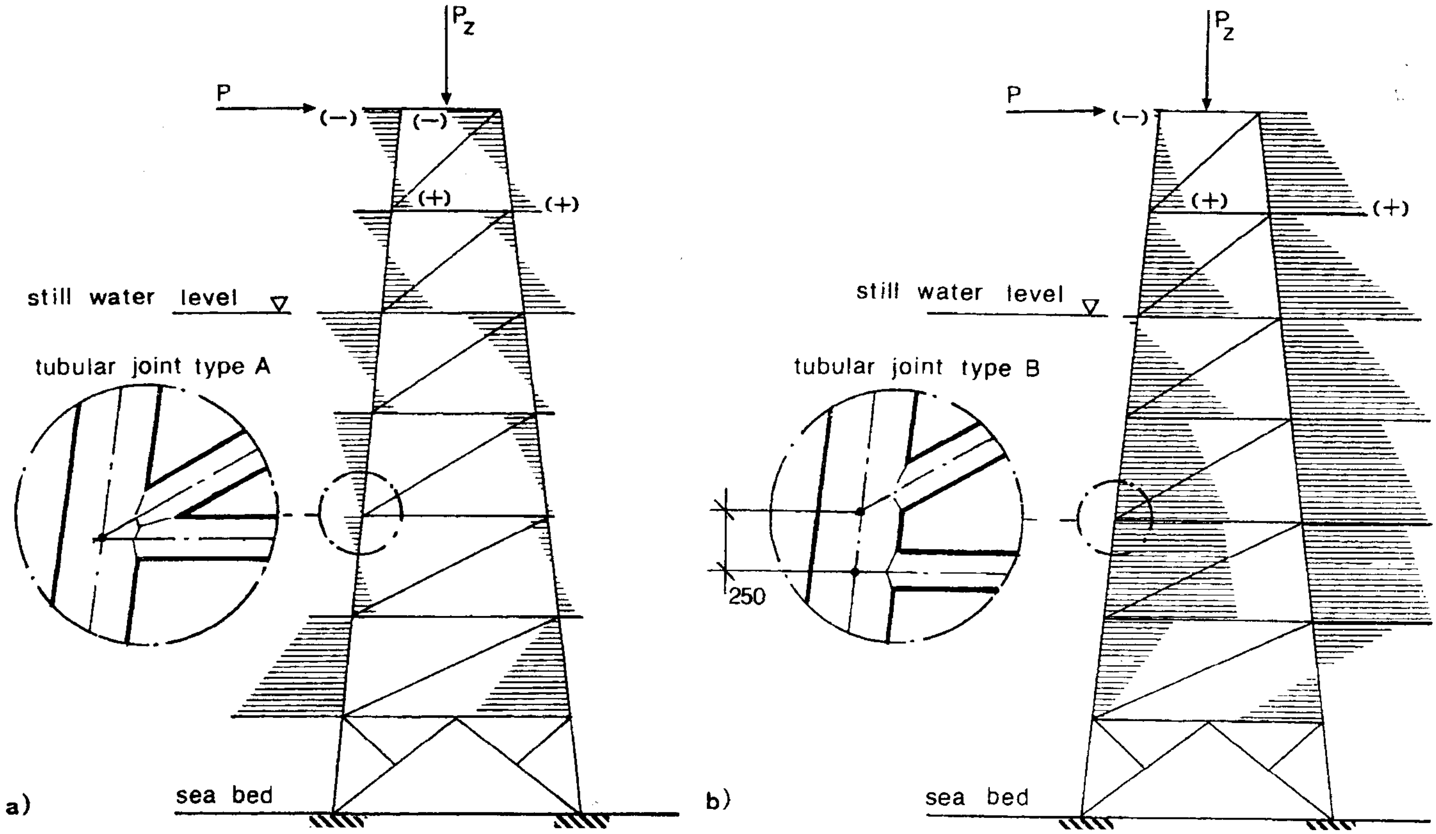


Figure 17.36 Bending of Fixed Truss

Joints must transfer stresses from one member to another. Continuity of material is sometimes difficult to attain and forces may have to be transmitted by bending of the tube wall. In addition weld toes may create local stress concentrations. Round tubulars of a smaller diameter are particularly vulnerable in this respect. Figure 17.38 from reference 31 clearly illustrates these points. The connection of r~und - members to plated structure also is sometimes rather oomplicated. Nearly always they make use of well-rounded brackets in line with the axis of the tube. The brackets slot into the tube walls and line up with plate members in the plated hull structure. The brackets are cut back deeply so as to minimize the stresses at the bracket toes, in order to reduce as much as possible the risk of fatigue. The brackets may be completely inside the structure or be visible from the outside.

Insight into the behavior of trusses can also assist in designing normal stiffened plate structures. Modeling in the designer's mind a structure as a truss may help to find an effective and optimal structure.

Example 26-0ptimal stiffening. Figure 17.39 shows the bulkhead of the pontoon used to raise the Russian submarine *Kursk.* The pontoon had to be modified and it was found that the subject bulkhead was overloaded in shear. Instead

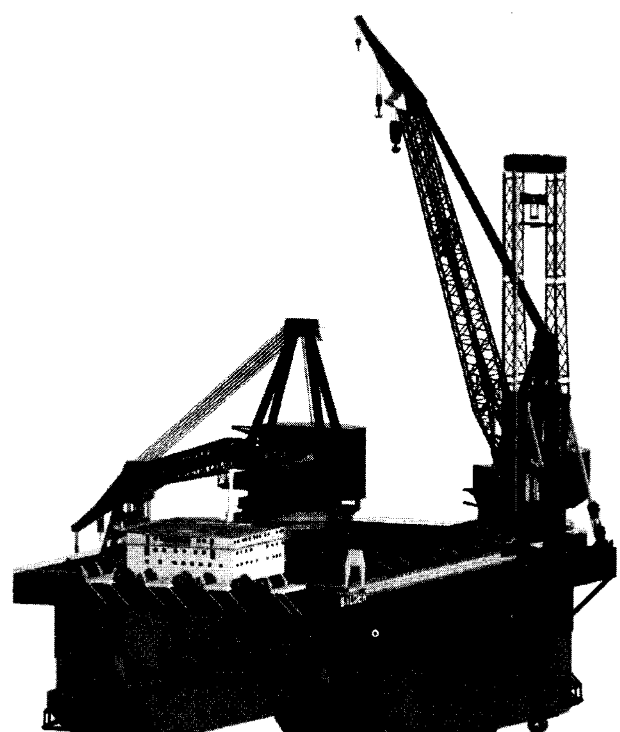


Figure 17.37 Heavy-lift Semi-submersible

of replacing the bulkhead or trying to weld on a large doubler plate, it was decided to install diagonal stiffeners in such direction that they helped to transmit the shear force as if they were part of a truss.

17.9.9 Local Discontinuities and Stress Concentrations

In subsections 17.9.2 and 17.9.3 the behavior of plates loaded in their plane was discussed. It was mentioned that stress lines and the hydrodynamic analogue could be used advantageously to understand stress distributions in plates. With the behavior around a circular hole in a plate (Figure 17.4) it was shown that discontinuities in plates lead to stress concentrations. It was indicated that small-localized concentrations often could be accepted because of local yielding. In general textbooks formulas for the maximum stress can be found (assuming linear material behavior also for the maximum stress levels encountered). The maximum stress and the extent of the stress concentration depend not only on the magnitude of the nominal stress but also on the dimension of the discontinuity (for example, the diameter of the hole) or its minimum radius in a direction more or less perpendicular to the stress direction. A larger radius reduces the stress concentration.

Example 27-Shaping to reduce stress concentration. The comer of hatch openings in the uppermost deck of a cargo

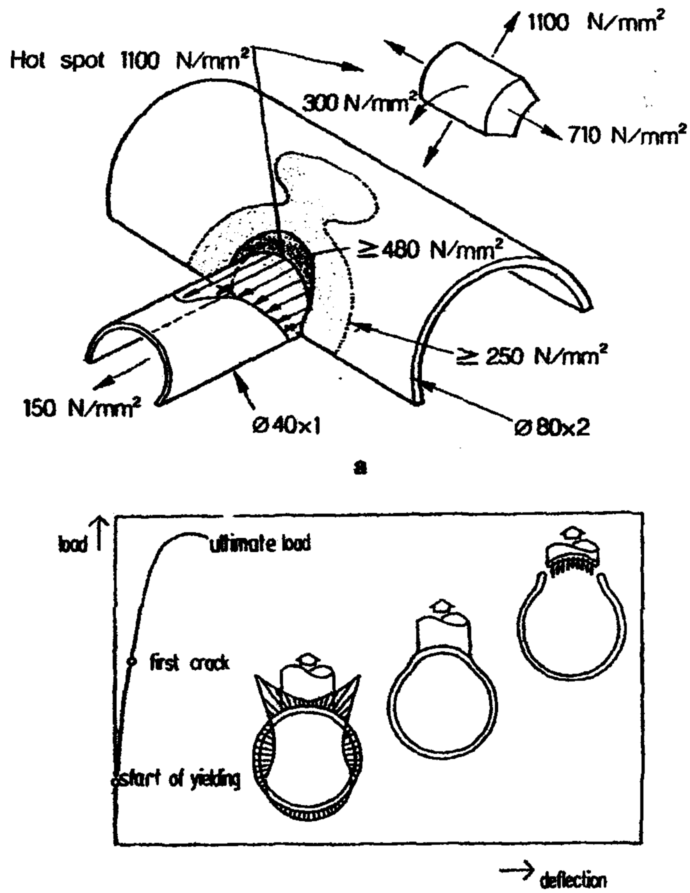


Figure 17.38 Stresses at Tubular Connections

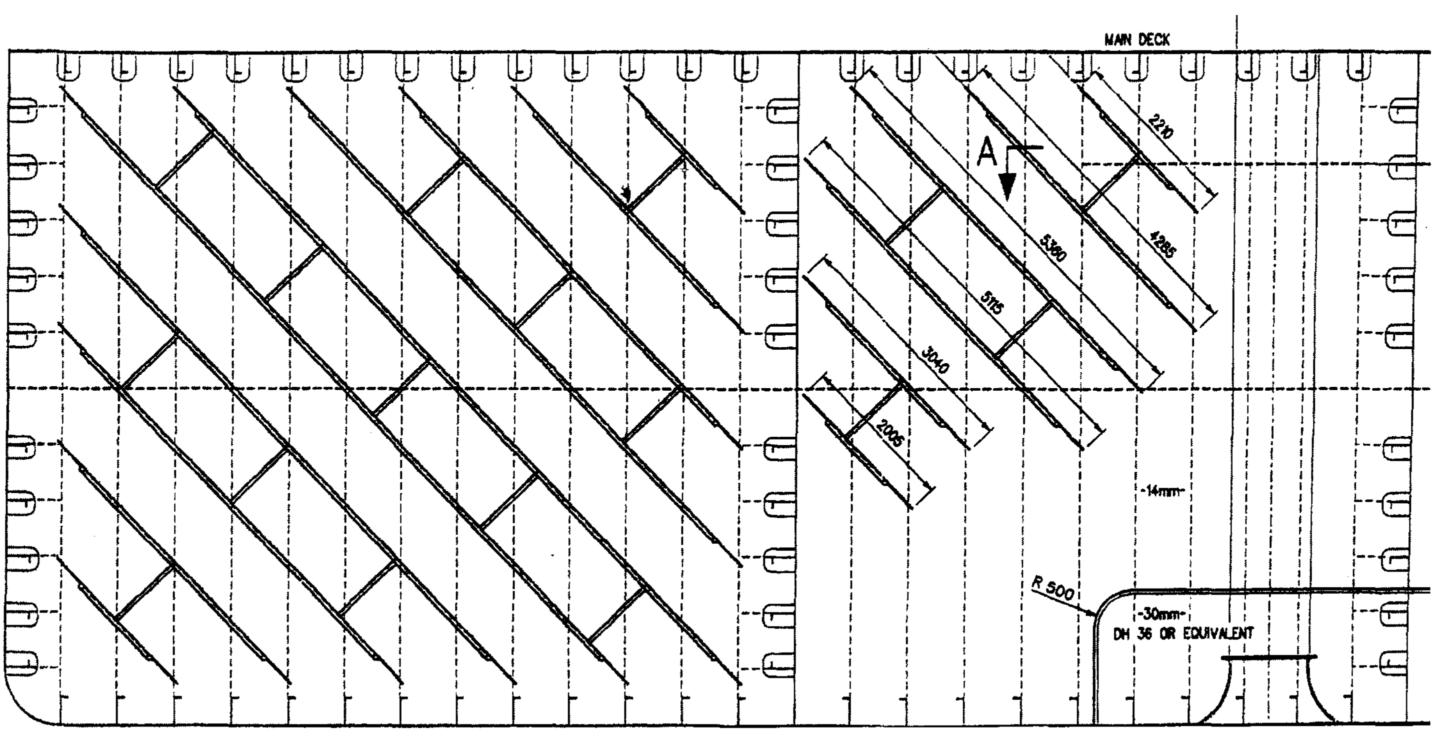


Figure 17.39 Diagonal Reinforcement of Transverse Bulkhead

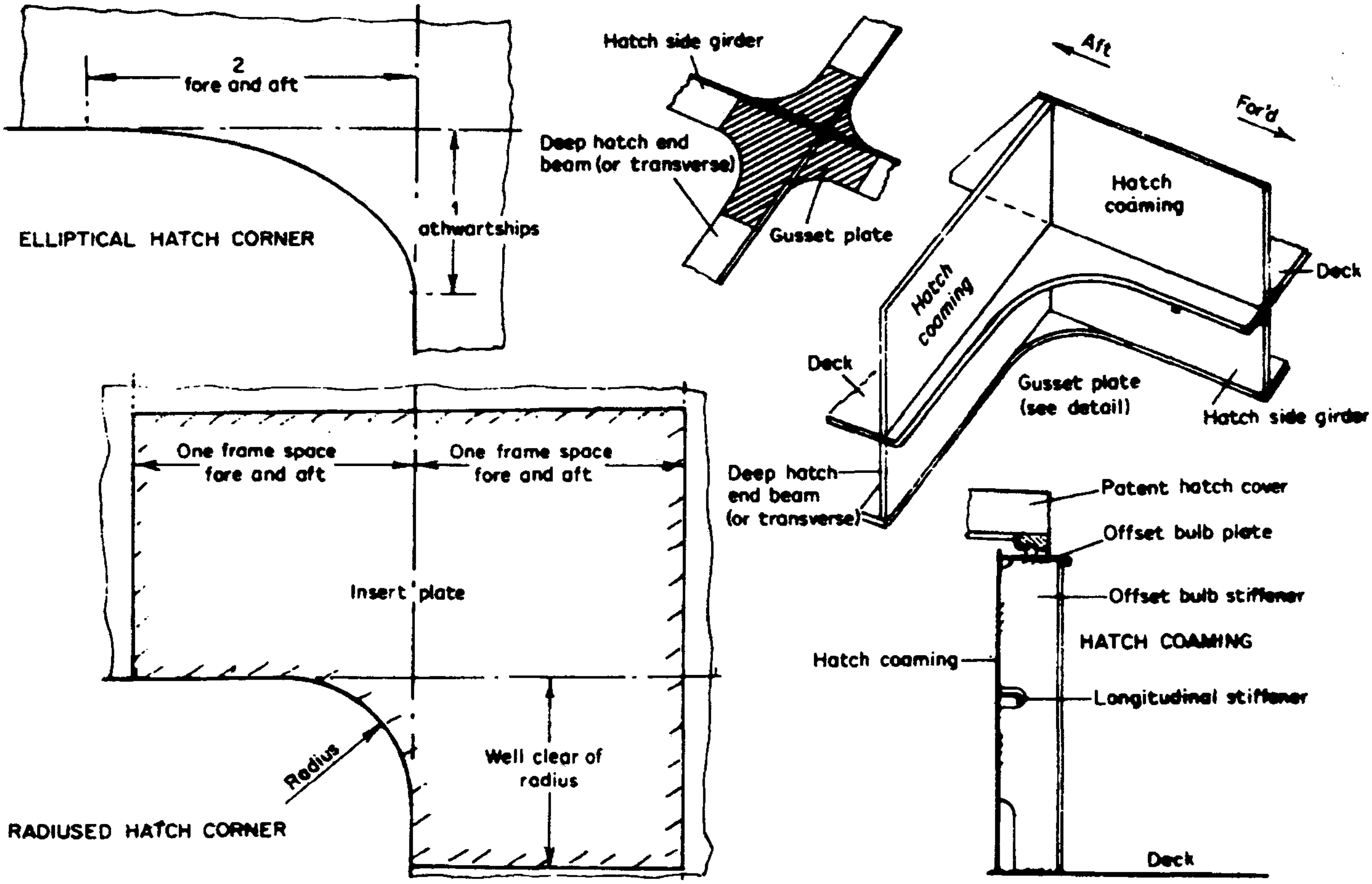


Figure 17.40 Hatch Corner Design

vessel is a typical example of a shape adopted to minimize stress concentrations. A rectangular hatch opening represents the most practical shape from the point of view of cargo handling. However, the sharp corner also causes a very-tigh stress concentration. In the Liberty ships in WW II this shape was a major cause for crack initiation, which in combination with weld stresses and poor steel properties lead to brittle fracture in several ships, sometimes even to complete breaking into two. Today provision of a fair radius in the corner of the hatch opening is common in the design of the hatch corner as shown in Figure 17.40 from reference 4.

Considering that the major stresses are in the longitudinal ship direction (due to overall bending of the hull) the main stress concentration will be located nearer to the longitudinal side of the hatch (relative to the ship's breadth) than to the transverse side. An elliptical shape of the corner as shown maximizes the radius at the point of the highest stress concentration without the loss of practical use of the hatch opening that a large constant radius would involve.

A common way to deal with stress concentrations is the provision of a thick insert plate. This is preferable to a doubler plate as sometimes still used (see example 30). The philosophy is that the same load transfer will result in a smaller average stress in this insert plate. The stress concentration thus will not lead to a too high local stress.

Example 28-Insert to reduce stress concentration. The hatch corner shown in Figure 17.40 has a thick insert plate to reduce the stress at the point of the highest stresses. Note that the use of a thicker plate is not always effective in reducing the stress concentration. It supposes that the load transmitted in the plate is not influenced by the change in thickness. However, as stated earlier, the higher stiffness inherent to the thicker plate, may attract stresses as well. In particular this will be the case when the structural part is subjected to an applied deformation rather than a load. In such situation the deformation remains more or less the same, hence the stresses, irrespective of the thickness. Another problem is that a thick insert plate may relocate the never be attained. Also note that if it were assumed that an *effective plate breadth be* may be defined as the total tensile force divided by the maximum stress at any cross section. This is as if all stresses are concentrated with the shaded distribution in the figure.

Example 31-Transition in shell. Figure 17.47 from reference 33 shows the transition of the side shell (and its bulwark) of a vessel to the superstructure somewhere at mid-length of the hull but also forward and aft. This is a construction that is used nearly universally when a superstructure at half-length is provided. The shape of the transition assures the minimum possible stress concentration at this location because of the large radius provided. But maybe at least as important is that it allows a gradual flow of the stress into the superstructure. From the point where the superstructure deck begins (at the end of the transition piece) the stress still has to distribute over the full width of the deck, which will require some distance (the shear lag phenomenon). Only then the superstructure becomes fully effective in accommodating the longitudinal bending moment of the ship.

For that reason a short superstructure is not considered to contribute to the vessel's longitudinal strength. The transition provided helps to overcome some of the shear lag and thus helps to increase the longitudinal strength.

Shear lag not only plays a role when the loads are inplane, but also in case of lateral loads. Shear lag then is associated with the introduction of the bending stresses from the web of a stiffener or girder into its effective plate flange. **In** that way it leads to the concept of effective breadth of the attached plate. A full description of the concept and the results for various loading conditions can be found in for instance reference 34. ~

A consequence of this is that generally the effective breadth of the attached plating is at its maximum when also the bending moment is maximal. This means that in setting up a structural design the designer must be aware of the phenomenon, but appreciate that it will not influence the concept.

In many ships such as tankers, container vessels, double-hulled bulk carriers and trailing suction hopper dredgers, longitudinal bulkheads over practically the full depth exist in the cargo part of the hull. These long bulkheads participate in the longitudinal strength of the vessel. But they are often not continued in the fore and the aft part of the hull (fore peak, engine room or similar). Where they stop against a transverse bulkhead, stresses must be transferred from the longitudinal bulkhead to the deck and bottom plating. The designer may be tempted to just continue beyond the transverse bulkhead with a stiffener along deck or bottom in line with the longitudinal bulkhead. However, just as with the bulwark in the previous example, this would lead to high stress concentrations at the transition. Again large br:ackets, preferably well rounded, in line with the longitudinal bulkhead, help to reduce the stress concentration and make the longitudinal bulkhead more effective (suppression of shear lag effect).

Example 32-End of longitudinal bulkhead. The aft end of the longitudinal bulkhead of a container vessel is shown in Figure 17.48 from reference 35.

At a large scale (regional) an abrupt change in material cross section is avoided by the long inclined transition in the bulkhead. More local stress concentrations are avoided by rounding with a fair radius. **In** the upper part the fairing has an even still better elliptical shape.

Note the soft toe at the end of the coarning bracket.

This *structural continuity* in order to avoid stress concentrations is one of the leading principles in structural de-

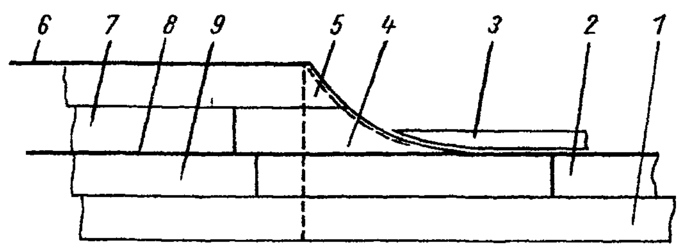


Figure 17. 47 Superstructure/Side Shell Transition

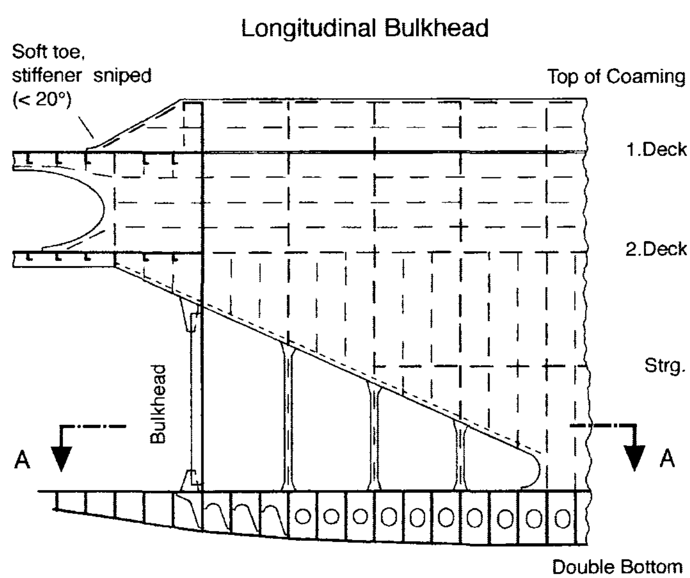


Figure 17.48 Aft Ending of the Longitudinal Bulkhead in a Container Ship

sign. As shown in the example, it is applicable at different scales, for large structures, as with the continuity of a bulkhead as just described, but also at the ends of girders or a stiffener. In everyday terms: stresses must be guided smoothly from one structural component into another.

Continuity is important at even smaller scales than those in example 33. Consider two intersecting plates. By nature one plate will be continuous. The other is not and the two sides may be found unintentionally to be slightly out of alignment. Any tensile (or compressive) force in the two members exerts a rotating moment on the connection. This moment normally will be counteracted by bending in the four plates (or better: half-plates) coming together in the connection. The magnitude of the bending stresses thus generated depends on the amount of misalignment. But even when this is only a fraction of the thickness of the constituting plates, the bending stress may be equal to or larger than the plate stress, which nominally is applied. Stress that is fluctuating in character this may easily lead to fatigue cracking.

Avoiding non-continuous members is in many cases not possible, but careful thought is necessary to decide which member should be continuous. Generally a first consideration is the question of which member is more fracture prone. From fracture mechanics follows that a similar initial crack length is far more dangerous in a narrow plate than in a wide plate. Assuming similar stresses in both members means that mostly the narrow member will be continuous. When a thin and a thick plate cross each other generally the thicker one will be continuous. This is so because the thicker plate (with similar stresses) will carry more load and therefore it is likely that any fracture in it will be more ominous to the total structure. But it is also because a thicker plate is generally more susceptible to lamellar tearing. Possibly its fracture toughness is also less, making the ris\ of brittle fracture larger. Finally, but certainly not least irl'iportant, with a non-continuous thinner plate welding is less and probably of a better quality.

17.9.11 Introduction of Concentrated Loads

In the previous Subsections structural concepts and structural responses were dealt with primarily related to more or less distributed loads. In many cases, however, loads are introduced into the structure in a concentrated or localized form. The attachment of a towline to a vessel constitutes a concentrated tension force on the structure. The weight of a cargo module on a heavy-lift vessel or the weight of containers in a container vessel represent compressive forces. These can all be considered as external forces. But the load coming from the tieback wires on floating sheer-legs is an internal force in the ship. The distinction between internal and external forces is not always clearly defined and has only limited impact on the structural concept. More important is whether the load always acts at the same location or whether it can act at (many) different locations. Container supports are always at the same location, but supports for the deck cargo of a work vessel may be located differently for every job. In the latter situation any structural provision preferably should be located external to the normal structure, whereas provisions of a more permanent character may (also) be located inside of the normal structure. In both cases it must be decided early in the design whether to introduce the load mainly into one structural element or to distribute the load over more members. An important aspect in case of tensile forces (which can also be the result of counteracting an overturning moment) is the decision to make the material continuous through, for instance, the deck plating or to stop it and let the intermediate plate be continuous (see the previous Subsection).

These general aspects of the structural design for localized load introduction obviously will lead to designs that are very specific for each situation.

Example 33-Load introduction via a pad-eye. Figure 17.49 shows the support for a pad eye used for sea fastening cargo onboard of a heavy lift vessel. The location of the pad eye will be different for each new transport. All provisions therefore preferably must be above deck. The arrangement consists of two H-beams of such length that they span the distance between two permanent web frames. The load on the pad eyes is mainly horizontal. But because this force has to be transmitted by the deck plating, a moment in the vertical plane results. Vertical forces at the ends of the beams accommodate this moment. The moment is transmitted through the beams by shear forces and concomitant bending moments.

At frame 47 the vertical force is transferred into the web plate by a gusset plate above the deck in line with the web. At the forward end, at frame 48, the existing bulkhead prevents the use of a similar gusset plate. Here bending of the deck plate must transfer the vertical force.

This is acceptable because of the proximity of the beam end to the web frame (and bulkhead). The horizontal force is transferred into the deck plate through the welds, which are provided only at the ends ofthe H-beam. Note that care must be taken to let the gusset plates line up with the web plates underneath, in particular when the transferred force is tensile (see also the previous subsection). In that case also the quality of the intermediate deck plating must be considered to prevent lamellar tearing. Similarly the weld attaching the web plate to the deck plate must be strong enough to transfer the force. Note that one beam necessarily must be intercostal. Although this might create a problem of struc-

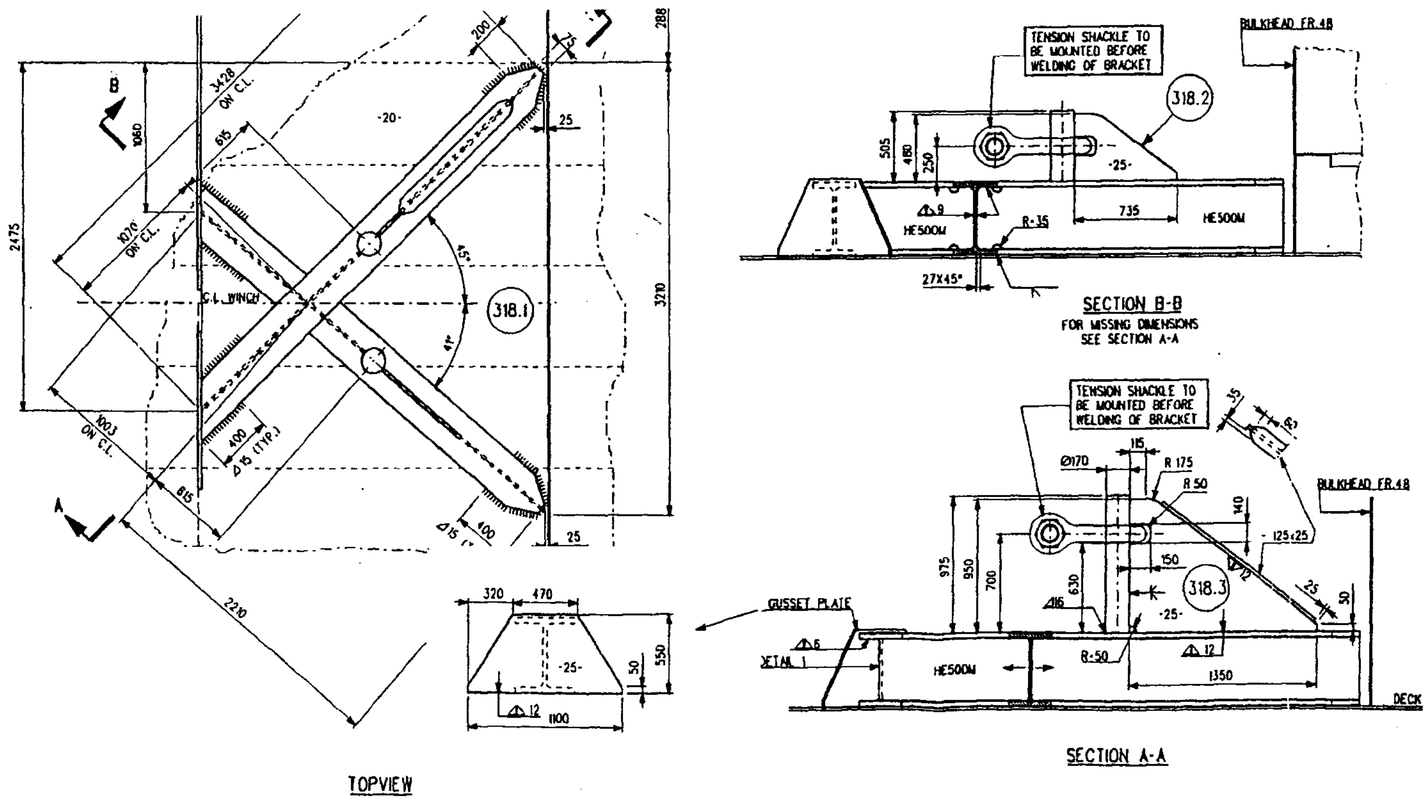


Figure 17.49 Pad Eye Back-up Structure

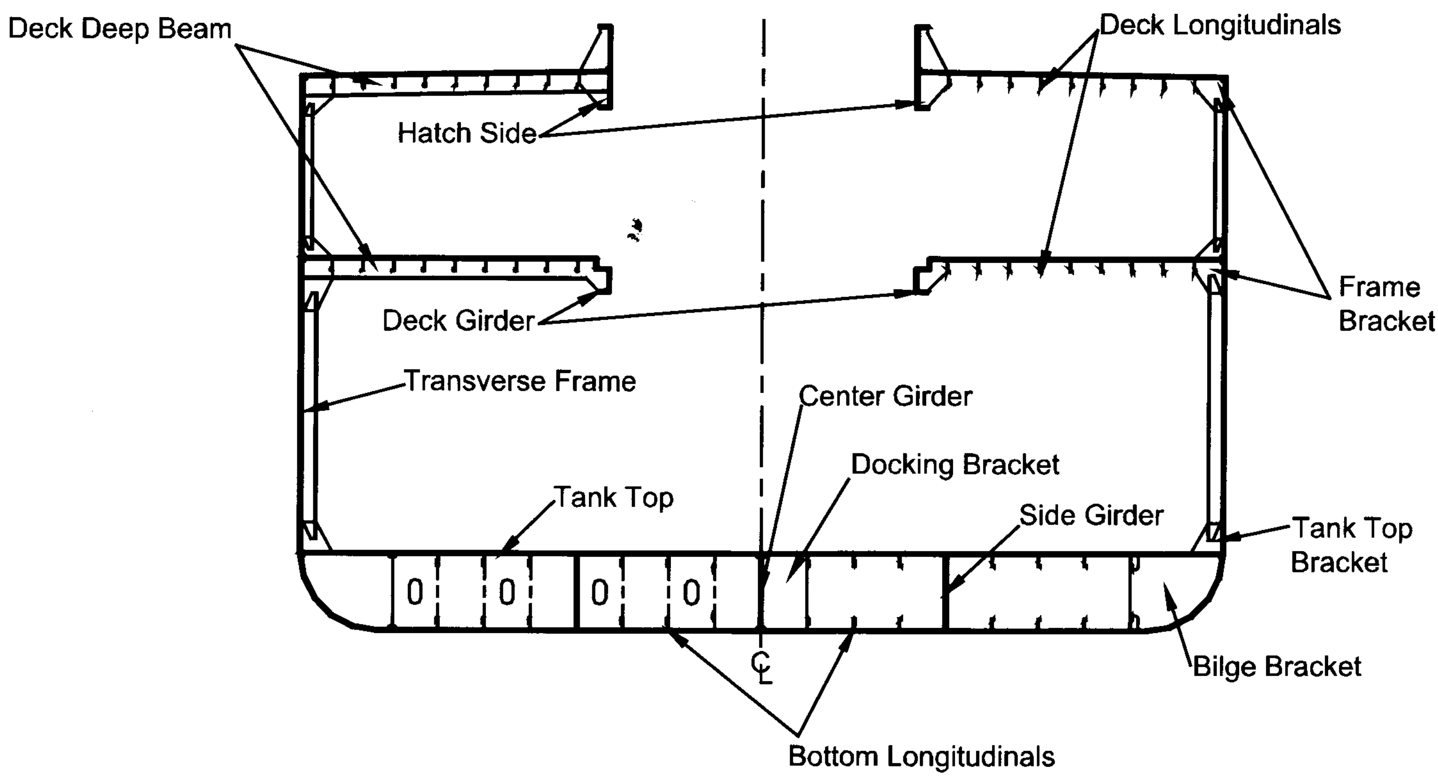


Figure 17.50 Typical Midship Section

tural continuity (as discussed in the previous Subsection) in the chosen design this is not the case.

17.10 OVERALLSTRUCTURAL ARRANGEMENTS, INCLUDING MIDSHIP SECTIONS

17.10.1 Midship Section Arrangements

The midship section is where the structural arrangement design commences. It requires only the beam, depth, draft, deadrise, and bilge radius to be decided in order to start. Thus it can be started as soon as the Preliminary Design (Chapter 5 - The Ship Design Process) is completed. Other information such as type of framing and major structural boundaries such as double bottom depth, tweendeck (if any) height, and location of longitudinal bulkheads will be available, usually from the Preliminary General Arrangement

The midship section is prepared with a half-section in way of floors or webframes on one side of the centerline and in between webframes and at open floors as shown in Figures 17.21, for a transversely framed ship, and 17.50 for a longitudinally framed ship.

Midship sections for other ship types are shown in other Chapters such as Figures 28.30, 29.36, 32.42, 33.13, 37.48, 38.17,39.9,39.10,39.11,45.32,45.37,45.38,48.29,48.30, 49.13, and 49.14 in the corresponding chapters.

The webframe, frame and longitudinal spacing may have been decided by the designer of the Preliminary General Arrangement and will be used by the structural arrangement designer. If not it must be decided at this stage. The decision will be based on major structural boundaries such as transverse and longitudinal bulkheads, decks, and flats. The spacing should be uniform in between the boundaries. The classification rules will give guidance on the spa6ng, but the final decision will be based on structural arrangements and shipyard preferences/experience.

The allowable spacing is less in the fore and aft peaks than the midship spacing. Also it may be less in the forward third of the ship length especially on high-speed fine hull form ships. The frame/longitudinal spacing should also consider production aspects for the shipyard (see Chapter 14 - DesignIProduction Integration), as should all other aspects of the structural arrangement design.

17.10.2 Scantling Plan

The next step after preparing the midship section is to prepare the Scantling Plan. This consists of an internal profile and deck plan views for the entire ship. It applies the structural arrangements developed for the midship section throughout the length of the ship taking into account changes to suit the ship general arrangement and the details that have been discussed throughout this chapter.

17.10.3 Hull Girder

In section 17.7.6 it was seen how the ship's hull consisting of shell and bottom plating, decks and longitudinal bulkheads acts as the main girder of the ship, often called its backbone. The hull and its constituent parts play an important role in the transmission of loads from one point to another in particular insofar as the load path is in the longitudinal direction of the ship. Vertical loads are the most important although horizontal and torsional loads can be important as well.

Vertical loads represent the situation that normally is related to the longitudinal strength assessment of the ship. The hull girder often is looked upon as a vertically loaded simple beam. The beam behaves as a so-called *Timoshenko beam,* meaning that it deforms under the external loads mainly in bending and shear.

In bending it is assumed that the transverse cross sections of the beam remain-plane and undistorted and perpendicular to the neutral axis (17). This assumption leads to the well-known standard linear stress distribution over the height of the hull girder. The effects of other loads than bending, that is, shear and torsion, lead to situations where the cross sections no longer remain-plane. But normally the effects of such other loads and those from bending are considered independently and the total response is considered to consist simply of the sum of the responses to the individual loads. Together with the moment of inertia Ixxof the cross section, responses like bending moments, shear forces and deformations can be determined using basic beam theory. This longitudinal strength calculation ofthe ship's hull is dealt with in many standard textbooks on ship structures (36) and in Chapter 18 - Analysis and Design of Ship Structure. This chapter will not repeat this theory, but only review it in Figure 17.51 from reference 33. Basically this approach is not so much part of the conceptual design of the structural arrangement. It is a first and very important analysis to check initial scantling estimates for a structural concept that has been arrived at based upon other considerations.

However, the assumptions that underlie the longitudinal strength assessment are fundamental to the structural designer when setting up the structural concept. In particular the assumption that plane cross sections remain plane and non-deformed under load is not always true. In some cases special care may have to be taken to assure that this assumption holds true. In other situations the assumption will never be true and this may have consequences for the structural arrangement.

Shear lag and effective plate breadth may also result in the overall bending stress distribution being different from what would be expected based upon the theory of considering the ship hull as a simple beam. In particular this is true for all sorts of novel hull shapes.

Example 34-Non-linear stress distribution. In Figure 17.52 from reference 37 the distribution of stresses due to longitudinal bending of a catamaran is shown. It is obvious that this is quite different from the linear stress distribution as assumed in the traditional beam approach. In particular the upper deck participates far less in accommodating the longitudinal bending moment. Partly this is due to the ineffectiveness of the superstructure side shell due to the many windows therein. It is also the consequence of shear lag in the upper deck itself due to which length is needed before the upper deck really becomes effective. This causes the decrease in stress level when moving away from the side shell. The small increase in longitudinal bending stress near the ship's centerline is caused by a longitudinal girder under the upper deck at that position. This girder is firmly attached to the lower part of the vessel hull at the fore and aft ends of the superstructure. If it were not so attached, the effect of the girder on accommodating the overall bending would not be possible. Note that making this central girder effective (to some extent) again illustrates how the designer can influence the effectiveness of the structure.

Also for more traditional hulls non-beamlike behavior may be the case. Many ships possess a more or less intact deck closing the top of the hull. Of course such deck often contains many openings. Hatches for cargo handling are generally the largest. Ifthey are very large the vessel is considered of the *open deck* type, which leads to some ~cial aspects that are considered in subsection 17.10.5.

17.10.4 Closed-deck Ships

Many deck openings are for passenger and personnel access, ventilation, exhaust uptakes, pipe runs, etc. The size of all these openings is such that their effect upon stresses and deformations is considered to be local and can be dealt with separately after first the overall strength of the hull is considered as if the hull were completely closed.

Many ship types have a closed deck, for instance, tankers, cruise liners, fishing vessels, naval vessels, heavy-lift vessels and ferries. General cargo ships used to be of the closed-deck type with relatively small hatch openings, but since the container became the normal way to transport cargo the corresponding ship is of the open-deck type.

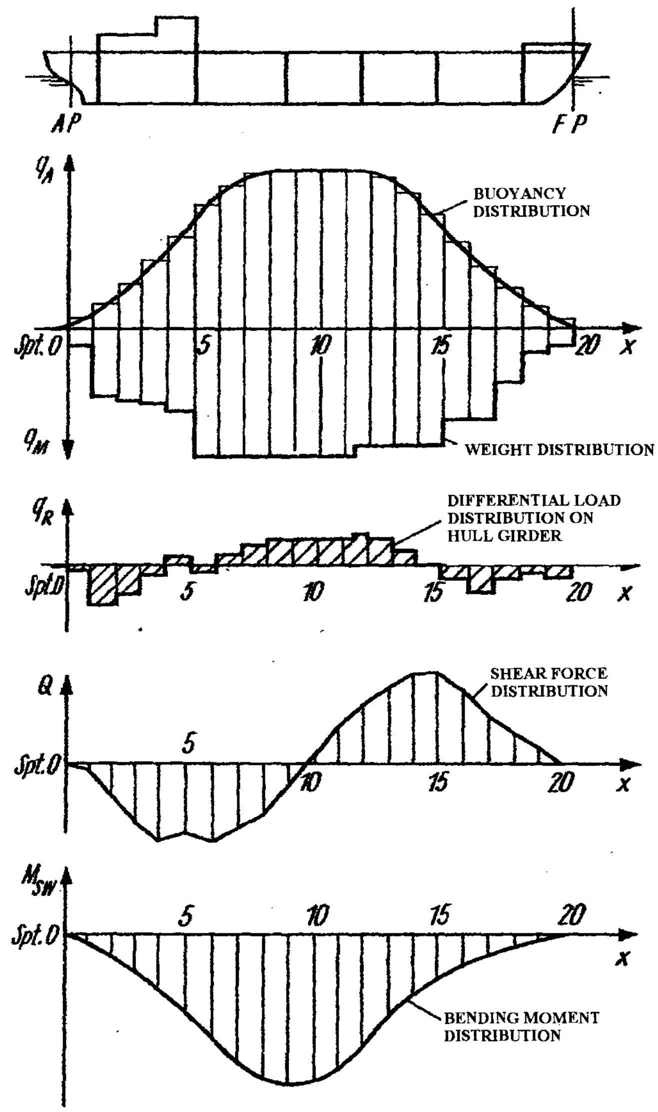


Figure 17.51 Review of Longitudinal Strength

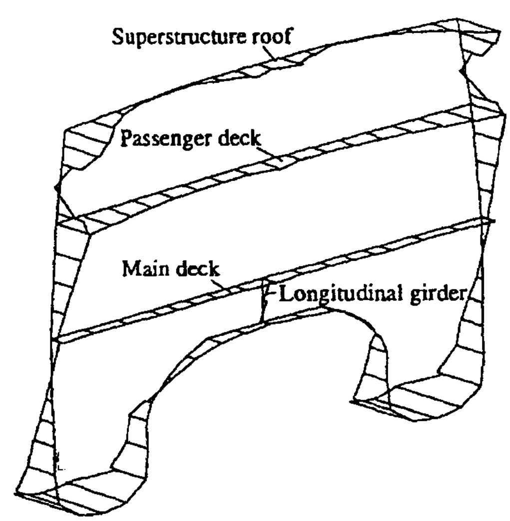


Figure 17.52 Stress Distribution in Catamaran Due to Longitudinal Bending

17.10.4.1 Single-deck ships

The most obvious closed-deck ship is the (crude oil) tanker. As they are also the largest of all ship types and possibly the most numerous, this Subsection will focus on those vessels. A full description of tankers, their operational characteristics, their layout and the regulatory requirements they have to comply with can be found in Chapter 29 - Oil Tankers. Tankers typically have a single deck. They possess a large cargo and ballast tank capacity. At the aft end is the engine room, above which is located the accommodation superstructure. The main structural change over the past two decades has been the introduction of the double-hull. This change, however, was not triggered by structural considerations but by the intention to minimize the risk of environmental pollution in case of collision or grounding. Yet the change has several structural implications as illustrated hereafter.

Figure 29.36 shows a typical midship section of a double-hulled tanker. Compare this with a typical single-shell tanker shown in Figure 17.31. The existence of the double shell and bottom in the new version is obvious. In the bilge area the inner shell plating is inclined mainly because in this wayan efficient solution is found to provide a gradual change from the double side shell to the double bottom structure. The structure now provides a large bracket between the shell structure and the double bottom. In the single-hull structure crossties were provided to connect the webframe at the shell to the vertical web on the longitudinal bulkhead. In the double-hull structure such crossties are provided in the central tank when two longitudinal bulkheads are provided. They now connect the web structure ofthe two longitudinal bulkheads. Webframes of the side shell carried the lateral load from sea and tank contents from the longitudinal stiffeners to the deck and bottom structure of the vessel. By connflfting the longitudinal bulkhead and the shell webs by one or two crossties, some of that load could be transferred via a shorter path; the load of a full tank at the shell compensated to some extent the load exerted on the longitudinal bulkhead. With empty tanks the web on the shell was supported to some extent by the web on the bulkhead. The web structure in this way could be lighter than without the crossties. The double-shell structure, being a sort of sandwich, is by nature much stronger than the old webs. Therefore such support of the shell structure is no longer needed. Instead it is beneficial to support the span of the webs on the longitudinal bulkheads as shown in Figure 29.36.

The distribution of vertical/longitudinal (bulkhead) material over the width of the vessel is quite different from that for a single-shell tanker. It is this material that must transmit the shear force resulting from unequal distribution of hull and cargo weight and buoyancy. The effectiveness of the various bulkheads and shell plating consequently will be quite different from that in a single hull tanker.

Another aspect that may be noted in Figure 29.36 is that a horizontal and a vertical plate girder support respectively the upper and lower knuckles of the inner shell plating in the bilge area. This makes it possible that transverse loads in the bottom tank top plating and the inner hull can be in equilibrium and hence a bending moment can be transferred from bottom to double-hull structure and vice-versa. Without those plate girders the effectiveness of the side shell and bottom transverse for bending in the bilge area would be less. Note the stiffener system on the large brackets connecting the longitudinal bulkheads to the bottom and deck transverses. These stiffeners are intended to reduce the risk of plate buckling for those brackets. The manholes in the double shell structure are provided with vertical stiffeners in order to reduce the risk of buckling of the free plate edges of the hole. In the double bottom the manholes have such stiffeners only at the side of the highest bending stresses.

The double-hull structure shown in Figure 29.36 is rather traditional and uses longitudinal T-bar stiffeners supported every few meters by webs. In the relatively small width of the double-hull this makes a rather complex structure, which is not easy to fabricate. Partly to overcome this disadvantage a unidirectional side shell structure has been developed (39). An added advantage of this construction is that it offers a smaller number of fatigue-prone details in the structure. And finally, it probably is better suited to accommodate extreme loads, such as those from collision.

The tremendous growth in size of tankers over the past decades together with the improved capabilities of computer-assisted analysis have led to structures in which high stresses are far more common than in the older tankers. At the same time and for the same reason of weight saving, higher strength steels have become a common construction material. This has caused many fatigue cracks, in particular at the intersections of longitudinals and bottom transverses and side shell webs. This numerous details in tanker construction have seen several new designs to reduce the risk of crack initiation. One is described in section 17.12.2.

Ship types, such as fishing vessels, tugs, among others, also possess one deck that is mainly closed. Bulk carriers have one deck (plus a double bottom), however this time with large hatch openings.

Example 35-Midship section of heavy-lift vessels. Figures 51.13 and 51.14 show midship sections of heavy -lift transport barges. Such barges are also of the closed single-deck type. The main structural aspect is that no cargo has to be stowed in the holds. This allows the use of structural elements that in other vessels would be unacceptable. In Figure 49.13 diagonal crossties are used to support the web and the knuckle of the bulkhead.

This type of vessel is characterized by the possibility of very high point loads stemming from the cargo on the deck. These loads then must be distributed over the width of the vessel, which may lead to very high shear forces to be transmitted by some structural components. The structure must be adequate to accommodate these forces.

17.10.4.2 Multiple decks

Many ship types have more than one deck. Generally the reason is that stowage of cargo or accommodation of passengers is best done within a limited deck height. Decks other than the main deck tend to lie close to the mid-height of the hull and therewith near the neutral axis of the hull girder. Therefore their contribution to the longitudinal strength of the hull girder is limited. Consequently the structural role of the tweendecks is mostly limited to accommodation of local loads, in particular cargo weight.

Example 36-A reefer midship section. Figure 28.30 shows the midship section of a reefer cargo ship. Several assertions of the present chapter can be seen in this figure in addition to the comments made in Chapter 28 - Reefer Ships. First of all it represents a multiple-deck cargo ship. It is a combination framed ship in that longitudinal framing is used for the main deck, and the bottom structure and the tweendecks use transverse framing. This is done mainly to eliminate deep web frames in the cargo spaces (holds and tweendecks), which would impede the effective stowage volume. For the same reason the connection between tweendeck frames and side shell frames is bracket1ess.

The detail shown in the figure involves high accuracy in construction as well as fitting of chocks backing up the connections of frame to beam. As an alternative, for ease «fabrication, the angles used for the deck beams and the shell frames can have their flanges pointing in opposite directions. The localized stress concentrations resulting from this when transferring the bending moment, is acceptable because the moment is not extremely large and is rather static.

The pillars are tubular members with a square cross section, making it easier to provide at least some structural continuity (see the inner bottom longitudinal in line with the pillar and the double floor plate stiffeners in line with the edges of the hold pillar). In most cases a girder would be located below the line of pillars. Note that although the pillars are in line, there is limited continuity between the various pillar sides at each level due to the different dimensions of the pillars. Doubler plates at the various decks provide the load transfer.

The bottom and main deck longitudinals pass through the plate floors and deck transverses, respectively, using rather wide slots. Shear forces are transferred via chocks overlapping the plates and connected to the web of the longitudinal. In the vicinity of the pillar landing on the double bottom relatively high shear forces may be expected. For that reason no access holes are provided in the floor adjacent to the pillar. The nearest manholes are provided with a stiffening ring in order to avoid risk of buckling of the free edges of the access hole under influence of the shear load in the floor. Finally, the longitudinals in this area are connected to the floor plating with double chocks, thus increasing again the shear area of the floor.

17.10.4.3 Longitudinal and transverse framing

The previous two subsections briefly mentioned longitudinal and transverse framing. Framing in general means a system of stiffeners on the bottom and side shell, decks and longitudinal bulkheads intended to accommodate lateral loads transferred onto the frames by the plating and to transmit those loads to web frames, girders and similar stiffer elements. They are part of the orthogonal stiffening system described in Subsection 17.9.7.

Two systems exist with regard to the orientation of the stiffeners. Figure 17.53 shows a transverse framing system, and in Figure 17.54 a longitudinal framing one.

Although longitudinal framing has been used in some cases at the start of building iron and steel ships, the transverse framing system was the universal system up till the 1950s. Today transverse frame spacing still is used as the fundamental dimension for numbering the location of frames, transverse webs and floors even where, because of the use of longitudinal frames, such location has very limited or even no structural meaning. Sometimes intermediate smaller structural components are located on the frame numbers.

Example 37-0penframe brackets. In the right-hand side of Figure 29.36 in Chapter 29, small brackets are shown between the lower end of the longitudinal bulkhead or the outboard double-bottom girder and the adjacent longitudinal stiffeners. Those brackets are located at frame numbers where no major structural components such as plate floors are provided.

The main advantage of transverse framing is that the shape of the frames is easier to fabricate than would be the case for longitudinal framing, where the longitudinals often have to be twisted as well as bent in two directions. This is particularly so for smaller vessels. In larger vessels with a long parallel midbody the longitudinal frames can remain straight, making fabrication relatively easy. However, this cannot be maintained into the fore and aft ends, unless the ship has a very simple hull form, and ships with longitudinal framing generally have transverse frames in their fore and aft ends.

The advantage of longitudinal framing is that the cross sectional area of the stiffeners participates in the overall strength of the ship. Thus the longitudinals will carry part of the longitudinal bending. The distribution of the bending stresses over plates and longitudinals is practically in proportion to their respective cross sectional areas. This double role of the bottom and main deck stiffeners leads to a reduction in steel weight used for the vessel construction.

Longitudinals generally transmit their loads to transverse plate floors or deck transverses, which are located at distances of 3 to 5 nominal frame distances. The plate floors and deck transverses in turn transmit the loads to the side shell and/or longitudinal bulkheads. Transverse frames transfer their loads to longitudinal girders (among which is the vertical keel) on the bottom and under the deck. Note that in vessels with a very long hold the longitudinal girders can be effective only when they in turn can transfer their loads again via transverses to the side shell and longitudinal bulkheads, if any. This is one of the reasons why a transverse framing system uses plate floors in addition to the open floors (consisting of profiles and brackets).

Example 38-Load transmission in a bulk carrier. Figure 33.13 shows the midship section of a normal bulk carrier. The double-bottom structure consists of a longitudinal framing system. The lateral water pressure on the bottom and the cargo load on the tank top are transmitted by the stiffeners to the transverse floors, which in turn transfer these loads to the side shell structure. However, we also note a considerable

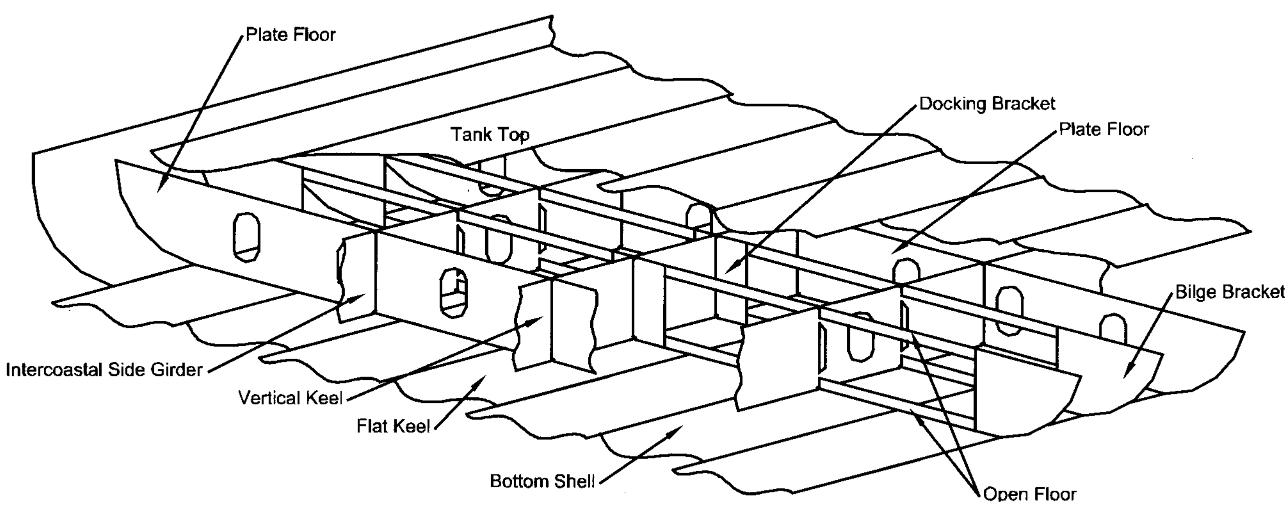


Figure 17.53 Transversely Framed Double Bottom

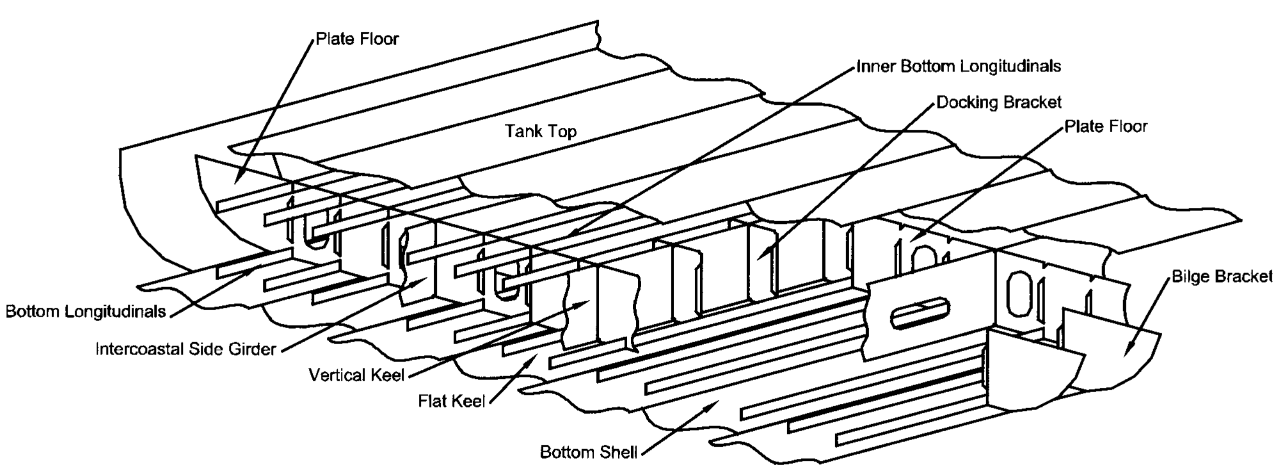


Figure 17.54 Longitudinally Framed Double Bottom

number of longitudinal girders. These are even more visible in the finite element model shown in Figure 33.14. From this figure it is clear that the span of the transverse floors between the bilges is of the same order of magnitude as the span of the longitudinal girders between the transverse bulkheads (rather short cargo holds). Transverse floors and girders consequently have a similar stiffness and, in accordance with section 17.7.5, they both will participate in transmitting the lateral load on the double bottom in a similar amount. Note that the stiffeners do not transfer their load directly to the girders, but may do so with the transverses as an intermediate member. The transverses and girders together may be considered as a grid as described in section 17.9.7.

In many cases the load transmission role of the girders in bulk carriers is even more important. This is the case when the holds of the vessel alternately are loaded and empty. This loading raises the vertical center of gravity and gives better ship motions (rolling) than when all holds are partly filled. However, this way of loading of a bulk carrier leads to a typical saw-like shear force distribution in the ship's hull. The overload (more weight than buoyancy) at the location of each filled hold is compensated by the underload (more buoyancy than weight) at the location ofthe empty holds. An important part of the hull shear force therefore needs to be transmitted only over a short distance, that is, a hold length, rather than over a much larger part of the ship length, as is normal for other ship types. This means that the stiffest load path may be via the longitudinal girders instead of going via the bottom transverses to the (stiff) shell and then back via the transverses. In summary, the typical arrangement of the bulk carrier in combination with its special loading conditions makes the use of longitudinal girders much more effective than for most other ship types (see reference 33 and also section 33.2.4.4 of Chapter 33). Many other aspects of the structural design olbulk carriers can be found in sections 33.2.2 through 33.2.4 of Chapter 33 - Bulk Carriers.

17.10.5 Open Ships

The previous two sections dealt with ships having one or more mainly closed decks. Some of the hatch openings may be quite large, but the important aspect of such ships is that the hull girder will resist torsion mainly by behaving like a closed section (see Chapter 18 - Analysis and Design of Ship Structure). The deck openings have only a localized effect on the stress distribution as determined for a hull with closed section.

With open-deck ships this is no longer the case. Torsion of the ship's hull girder results in clear deformation of a cross section out of its plane.

The out-of-plane deformation of a cross section is called *warping.* In a container vessel, deck strips are provided between the holds with their large hatch openings. Under the influence of torsion such deck strips will deform as previously shown in Figure 17.5. The deck strips in this case are not strong enough to resist the warping deformation. Note that not only the deck strip is deformed, but also the hatch opening. They become slightly lozenge-shaped. High stresses in the hatch-opening comer are the result. Generally an elliptical shape of the deck plate in that comer is provided to reduce the maximum stress and the risk of fatigue. Also, this deformation has consequences for the way in which the hatches have to assure a watertight closure.

In many cases warping of open ships is restrained by giving parts of the hull a closed cross section. For container vessels mostly the fore and aft ends and sometimes a length around the engine room and deckhouse provide such torsion-strong parts. These parts will not warp so easily and will support the open structure. Making the transverse bulkheads partially or completely of a closed box-type con-

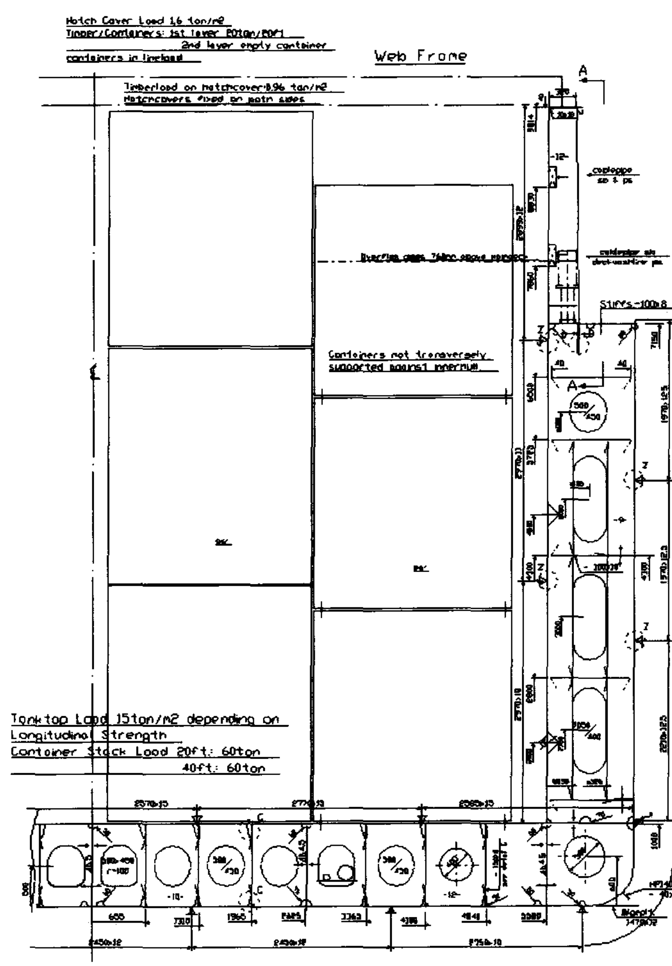


Figure 17.55 Midship Section of a Short Sea General Cargo Ship

struction will additionally contribute to reducing the warping of the hull girder.

Other examples of open ships are some types of general cargo short sea traders, heavy cargo vessels, and transport barge carriers.

Example 39-In-plane deformation of a cross section. The general cargo vessel for short sea trade is the successor to the coaster that existed in Europe over a large part of the 20th century. These vessels generally have one large, open, box-type hold. The dimensions of the hold are such that stowing of containers is easy (in the hold as well as on the hatches). These ships do not have container guides as larger container vessels do. In this way the hold is also suitable for many other types of cargo, including bulk. A portable grain bulkhead often can be placed at different locations in the hold for sub-division. But this bulkhead does not participate in the overall strength of the hull. A typical midship section for such vessel is given in Figurel7 .55. Obviously such a vessel is of the open-deck type. Torsional strength is partly provided by the double shell and double-bottom structure and partly by the torsion-stiff fore and aft ends of the ship. These latter prevent to some extent warping ofthe hold length of the hull. No torsion-stiff transverse bulkheads are provided, as often is the case in larger container vessels. Because of the lack of transverse bulkheads; however, another type of load and the corresponding deformation becomes important. The water pressure (including waves) on the side shell, often not compensated by a similar pressure in the hold, exerts a bending moment on the double shell structure. This is clearly illustrated in Figure 17.56 from reference 35, which shows the deformation of such a vessel under the influence of the water pressure.

The bilge structure of the vessel must transfer the bending moment from the side structure to the double-bottom structure. The bending moment may partly be compensated by the bending generated by the water pressure on the vessel bottom. Otherwise it may be transmitted by the double bottom to the opposite side shell and then compensated by the water pressure exerted on that part of the structure. Here is a clear example of a situation where the beam theory for the hull girder at least in one respect does not comply with the assumptions. The cross section does not remain non-deformed. Generally, however, the response may reasonably be approximated by assuming independent responses for overall longitudinal bending and local transverse bending. Stresses and deformations are then assumed to be the sum of the two responses for the individual load cases. But in

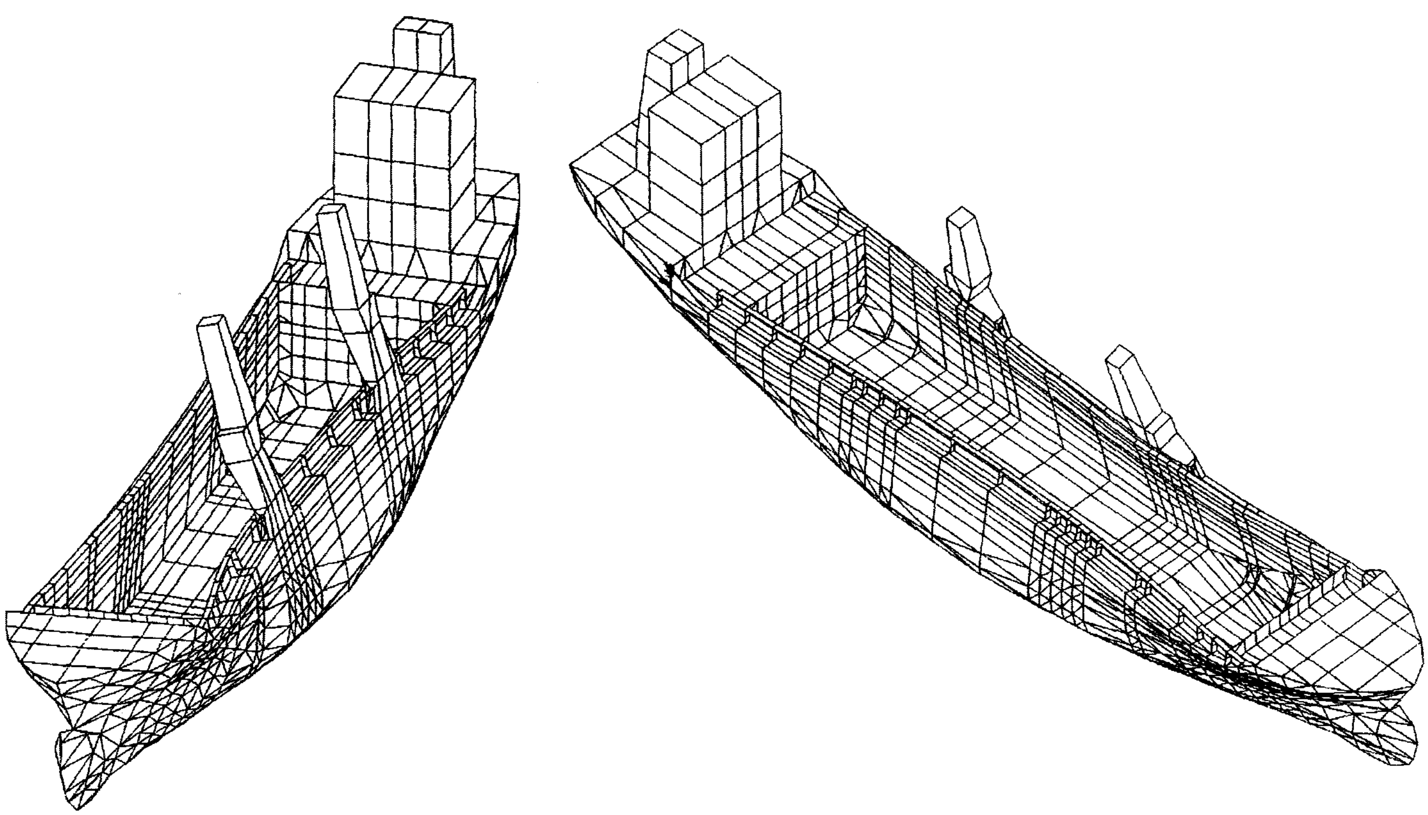


Figure 17.56 Hull Deformation Due to Water Pressure

exceptional cases this assumption may not hold true, for instance, where longitudinal bending (compression in the upper part of the hull) increases the deformation from the transverse loading. But the structural arrangement will normally be designed such that this is not the case.

The main dimensions are dictated by non-structural considerations: minimization of overall width of the vessel, a clear hold width related to a full number of container widths, a very large hatch coaming height in order to reduce the hull depth and thereby the tonnage (admeasurement), hatch opening and hold the same width for container stowage and handling, a sharp comer connecting the tanktop and the inner shell (again for container stowage considerations), etc.

No container guides are provided and the containers are not supported by the side structure. The tanktop and double-bottom are designed for a load of 15 tons/m^2 in view of heavy bulk or other heavy cargo.

The vessel has a longitudinal framing system to reduce steel weight. The long parallel midbody uses this system to achieve low fabrication costs.

As previously explained, the side structure must transmit bending moment stemming from the horizontal water pressure. The corresponding shear force is not very high. For that reason rather large access openings in the side webframes are acceptable. The vertical plate stiffeners run just outside these openings and thus provide edge stiffening. In this way they prevent buckling ofthe otherwise long unsupported edges of the openings. The access openings are so long that the behavior of the web plus inner and outer shell plating as one beam may be disputed. The vertical stiffeners provide buckling stiffness, but at the same time may also act as flanges on the plate adjacent to the access openings. This means that if these openings are too large to allow the side structure to act as one beam, they mayile replaced by two parallel beams at both sides with these stiffeners acting as flanges together with the outer and the inner shell respectively. Note that the vertical stiffeners stop at horizontal stiffeners in order to avoid hard spots on the plate. The horizontal stiffeners come so near to the vertical inner and outer shell plating that this does not result in hard spots.

As mentioned earlier, the bilge must transfer a bending moment from the side shell structure to the double bottom. The relatively small bilge radius helps to keep sufficient material in the web frame to be able to do so. In the vertical side shell the gradual increase in bending moment from top to bottom can be accommodated by an increasing effective plate width, giving the effective flange to the beam of the side shell structure. In the rounded plate of the bilge, however, the effectiveness of the plate adjacent to the web plate is far less because of shear lag. This reduces the capacity of the bilge to transfer the bending moment. It may be necessary to use intermediate bilge brackets in between the webs to increase the bending capacity. In such case attention must be given to the transfer of stresses from the webframe to the effective bracket.

The first panel of the plate floor in the double bottom near the bilge does not have a manhole because this would be too detrimental to the bending moment carrying capacity of the bilge structure. The second panel for the same reason has a manhole of limited dimensions. Some of the other manholes have a special shape to allow passage of piping. Note that the longitudinals under the tanktop cross the floor plates with a cutout on one side only. The traditional rathole for welding at the other side is no longer needed because of more accurate fabrication methods. The intersection of the bottom longitudinals with the floor plates still does have those ratholes, mainly to make possible a good drainage of the double bottom when being emptied.

Single hulls are a normal characteristic for many types of small craft. They may be of very simple construction in steel for many workboats or more complex in aluminum or composites for more advanced vessels.

Example 40-An aluminum patrol craft. A typical midship section of a high-speed patrol craft built in aluminum is shown in Figure 48.29 in Chapter 48 - Service Ships. A major consideration for the structural design of high-speed craft in aluminum is fatigue. The following points may be noted. The vessel has a longitudinal framing system. The frame spacing is quite small, only 250 mm. Such small frame spacing is common for aluminum craft albeit somewhat bigger (up to 500 mm) for larger vessels. The reason for this small frame spacing is minimization of the structural weight with a somewhat larger number of structural components and hence higher fabrication costs. At the same time the resulting small plate panel dimensions are beneficial for reducing weld distortions and thus improve the appearance of the vessel. In exceptional cases such distortions may even have a detrimental effect on the plate panel strength when loaded in compression. When loaded laterally, however, a beneficial effect may result from the then mobilized membrane strength. But normally panel deflections due to welding are to be avoided.

The stiffeners on shell and bottom consist of symmetrical T-sections. The use of such profiles seems to be partly influenced by the nationality of the designer or the shipyard. In Holland, for instance, bulb profiles are normally used instead of the T-sections. The advantage of the bulbs is that they allow a good intersection with the web frames. Only a close-fitting slot is arranged in the web to let the stiffener pass. Welding then is all around. Cutouts at the intersection are provided only if so required for drainage. The T-stiffeners shown in Figure 48.29 cross the webs through large cutouts. This arrangement contains a certain risk for fatigue damage. An advantage of the T-stiffeners is that they are less prone to sideways buckling or tripping under the influence of longitudinal loads or high lateral forces such as may be expected from slamming on the shell. Bulb profiles may require additional tripping brackets to prevent this. The deck stiffeners are smaller than those on the shell and bottom and therefore can be angle bars. Their intersection with the webs shows cutouts, including small ratholes, at the non-flange side. Those are provided to make welding easier. The effectiveness thereof depends on the welding system used. Today often a close fitting cutout is preferred. Modern welding systems guarantee a good weld even without the ratholes. Such detail then may give a better fatigue performance.

The web frame is continuous in the corners with large radius. To improve the fatigue performance of the web neither brackets nor overlaps are installed. The web detail around the spray rails as shown may be rather fatigue prone, certainly under slam loads. Improved details exist today. Note the tripping brackets (indicated by T.B. in the figure) on the web.

17.10.6 Multi-hull Ships

Chapter 44 provides an extensive description of catamarans and Chapter 45 of SWATHs and trimarans. These are typical examples of multi-hull vessels. But also semi-submersibles as used frequently in the offshore industry (see Chapter 42 - Offshore Drilling and Production Units) belong to this category. Multi-hull vessels have an even larger variety of structural concepts than is the case for more traditional vessels.

Whatever their details, a major aspect in the struct\1ral concept of multi-hull vessels is the joining of the various hulls. Generally the intention is to connect those in a largely rigid way. Some exceptions exist. In particular some FPSO-systems (floating production, storage and offloading systerns) as used in the offshore industry may have elements that are articulated connections, involving rotation in one or more directions between some of the elements of the structure. Such articulated vessels are so special that they are not further dealt with in this section.

The hulls, columns, upper decks and other large elements will experience external loads such as water pressure (static or as the consequence of waves or current), cargo weight, inertial forces due to accelerations or forces resulting from crane loads, drilling risers and so on. Contrary to mono-hulled ships those forces are not necessarily in equilibrium for each individual element. The resulting force per element must be provided by the connecting structure. For the vessel as a whole the connection forces are internal, but when an individual element is considered independent from the other elements, as will often be the case, they are external. Quite important forces may result from vessel motions. Those motions result mostly from wave action, which often is not exerted on the element under consideration. The forces must be transferred to that element by the connecting structure. Often the connection (nearly) only serves such a structural role, as is the case with a bracing system, but in other cases its primary function may be otherwise such as the upper pontoon, which provides accommodation. The kind of load that the connecting structure must transmit can be various; it may be a tension or compression force, a shear force or a moment around various axes. If the connection is for load transmission mainly, its arrangement may be optimized for the load to be transmitted. Often different structural components will be incorporated for the different load types.

Example 41-Brace system of a semisubmersible. In section 17.7.5 the case of the connection between the floats (pontoons or lower hulls) of a semi-submersible was used to illustrate the concept of parallel load paths. The force to be transmitted in that example is the so-called splitting force, a type of force that does not exist in mono-hull vessels. It is a fully internal force for the vessel as a whole and consequently is not important for ship motions, stability and similar. For the structural design of the elements of a multi-hull vessel this kind of load may be decisive. The connecting structure for the floats in this case comprises both the brace and the box like upper pontoon. The brace has a load transmission function only; the upper pontoon primarily provides accommodation.

Apart from the splitting force other forces and moments have to be transmitted from one float to the other. Important for many of the multi-hull concepts is the so-called pitch connecting moment. As the term indicates, this is the moment that prevents one hull pitching independently from the other. Fundamentall y this moment is also the major part of the total torsion (or twisting) moment acting on the vessel around a transverse horizontal axis. For instance, a torsion resulting from an unequal distribution of the weight and payload of the upper platform may be added to the total twisting moment. If no other connecting elements are provided, the total torsion may be accommodated by the upper platform. When this is a box-type plate structure, it is quite capable of doing so. Visualizing the deformations of the complete structure under such a pitch-connecting moment easily shows that the center of rotation will be inside the upper pontoon. The lower pontoons will then displace longitudinally relative to each other. At the same time this strongly suggests an alternative way of accommodating the torsional moment, that is, by means of diagonal braces in the horizontal plane between the floats. Such horizontal diagonal braces and the torsion capability of the upper pontoon constitute parallel load paths for the accommodation of the moment. The braces are the stiffer load path and will attract most of the total moment as explained in section 17.7.5. Analysis of the structural responses to a torsional moment will once again mean that the braces will become strong enough to accommodate practically that entire load. This does not mean, however, that omitting these braces and accommodating the total moment in the upper platform is not a viable structural concept. As mentioned earlier, the structural concept of many modem semi-submersibles is based upon this philosophy and only transverse braces are provided.

Secondary stresses in the connections of multi-hulls due to impressed deformations may be as important as the primary stresses resulting from load transfer. The following is an illustration of this. With only horizontal transverse braces in a semi-submersible, the vessel deformation under the influence of the torsional moment will result in a relative longitudinal displacement of the two floats. The transverse braces cannot prevent this but will have to follow that deformation. Because the braces may be considered to be clamped into the floats or the columns (whichever they are connected to) they will then get an S-shaped deformation (compare this to the deformation of the deck strip between the hatch openings of a container vessel as shown in Figure 17.5). The consequence is a bending moment at their ends. This moment changes in sign as the deformation of the vessel changes under the influence of the passing waves. This stress fluctuation combined with the structural stress concentrations that often are present in the transition from a tubular brace to the plate structure of a column or pontoon means that fatigue is a real threat. A fatigue cracl may have a quite high growth rate because of the rather small dimensions of a brace (compared to the dimensions of the plate structures present elsewhere in a semi-submersible). Moreover, a brace is a component the rupture of which may easily mean a serious threat to the structural redundancy of the vessel. All of this means that fatigue is an important aspect to be taken into account when designing a semi-submersible with horizontal braces only. In an exceptional case the braces were connected to the lower pontoons by means of large ball bearings in order to prevent the end fixing moment and therewith reduce the fatigue risk.

Apart from splitting forces and torsional moments the connection of the various hulls of a multi-hull vessel may be subject to still other forces. Racking is basically a shear force between two hulls. Mostly this is in the vertical direction, but horizontal racking forces may also exist. This may be accommodated with quite complicated space frames as already shown in Figure 17.33. If plate structures are used, care must be taken that they can transfer the loaqs to the components to which they are connected ..

Example 42-Rubber mounted superstructures. A typical cross section of a catamaran is shown in Figure 45.37 in Chapter 44. In order to reduce noise and vibrations, rubber pads are provided between the accommodation block and the two hulls. The load on these pads is a combination of the weight of the accommodation block, including passengers and luggage or other cargo, and the loads resulting from waves, uneven load distribution in the hulls, and similar. A certain bending moment will have to be transferred from the hulls into the accommodation block. A combined bending moment plus the vertical force may result in tensile forces or stresses at part of the connection. If so, the rubber pads, which probably are not designed for tensile loads, may not be a good concept.

As previously mentioned, redundancy may be another important design aspect when setting up the concept for a multi-hull. Probability of damage, likely extent of damage, and consequences of damage for the total vessel are among the considerations that have to be taken into account.

17.10.7 Submersibles and Submarines

Some vessels are characterized by their ability to spend most or a large part of their operational life underwater. Their operating water depth may be small to very large. Typical examples are naval submarines (see Chapter 54-Submarines), ROVs (Remotely Operated Vehicles) and deep-water exploration vessels. Although surface and above-water operating modes will have structural consequences, this mostly is in addition to the major design parameter, that is, the underwater mode. Note that the lower hulls (floats) of semi-submersibles and SWATHs may also be considered as submersible vessels (albeit for a limited design draft) and some structural concepts of submersibles may also be found in these parts of such vessels.

More than overall longitudinal bending, the water pressure existing all around the perimeter of the vessel cross section will be the main design parameter. To some extent this makes a submersible comparable to a pressure vessel. The pressure, however, is external, not internal. A simple equilibrium of pressure integrated over area divided by cross sectional area in a pressure vessel shows that the magnitude of the longitudinal stresses (that is, stresses in the direction of the vessel axis) is half of that of the tangential stresses (stresses in the direction of the circumference ofthe vessel).

Deep-water submersibles generally consist of a ring-way of accommodating the torsional moment, that is, by means of diagonal braces in the horizontal plane between the floats. Such horizontal diagonal braces and the torsion capability of the upper pontoon constitute parallel load paths for the accommodation of the moment. The braces are the stiffer load path and will attract most of the total moment as explained in section 17.7.5. Analysis of the structural responses to a torsional moment will once again mean that the braces will become strong enough to accommodate practically that entire load. This does not mean, however, that omitting these braces and accommodating the total moment in the upper platform is not a viable structural concept. As mentioned earlier, the structural concept of many modern semi-submersibles is based upon this philosophy and only transverse braces are provided.

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Deep-water submersibles generally consist of a ring-stiffened cylinder (Figure 17.57 and Figure 55.26 in Chapter 55 - Submarines). The stiffeners may be provided internally or externally on the shell of the pressure hull (as such structure is commonly called). Their primary role is prevention of buckling of the shell plating under influence of the external pressure (the possibility of which is the main structural difference between a pressure vessel and the pressure hull of a submersible). The spacing of the ring stiffeners must remain limited in order to optimize their effect for this role. By providing material in the tangential direction in addition to that of the shell plating, the stiffeners help to optimize the structural weight by reducing the essentially higher stresses in the circumferential direction, as mentioned in the previous paragraph.

In submersibles a large proportion of the external load is in equilibrium with the external load at the opposite side of the vessel. Much of the load will be transmitted in the form of membrane stresses in the shell plating and in longitudinal stresses in the ring stiffeners (the equivalent to membrane stresses in plates).

Example 43 -*A conventional submarine.* The cross section of a typical conventional submarine is shown in Figure 17.58. The vessel has two shells (hulls). The inner one with external ring stiffeners is the pressute hull containing all compartments that should remain under atmospheric pressure (accommodation, engine room, torpedo compartments, etc.). No longitudinal stiffening members are provided that shows the effect of membrane stresses in the shell plating and in the stiffeners.

The outer shell has internal stiffeners the scantlings of which are much lighter than those of on the inner (pressure) shell ring stiffeners. The space between the outer and the inner shell contains equipment and compartment, that can resist the high pressure in deep water such as the air bottles for emptying the diving tanks.

The diving tanks are also located outside the pressure hull, but this is because their internal pressure by definition is equal to that of the surrounding water. Locating the tanks in between the two hulls thus means minimizing their loads and thus their structural weight. The outer shell provides the (hydrodynamic) shape to the vessel. The inner and outer shells are connected by a series of relatively light struts to keep the vessel in shape.

Note that the vessel structure is designed not only to withstand the static external pressures but also the shock loads that may result from underwater explosions.

17.10.8 Jack-ups

Self-elevating platforms or jack-ups (see a full description in Chapter 43 - Offshore Drilling and Production Vessels) are special in the sense that they operate in two modes, that is, in the floating mode and in the elevated mode. Schematically the main forces and reactions at the sea floor for the elevated condition are shown in Figure 17.59. The legs are considered pinned at their lower ends at the sea floor or some distance below it. The horizontal hydrodynamic (waves, current) and wind forces in combination with the vertical weight, payload and force exerted by the drill string are in equilibrium with the vertical, horizontal and sometimes rotational reaction loads at the lower ends of the legs. The connection between the legs and the jack-up pontoon is considered to be rigid, meaning that the legs are modeled as beams with the rotation restrained at the connection to the pontoon. All the legs must have the same horizontal displacement at the pontoon level, leading to a redistribution of the horizontal loads on the legs via the pontoon. The resulting moment distribution over the length of the leg has a maximum at the leg top. This in turn means that the leg structure generally is heaviest at the top.

In the floating mode the legs are raised and extend far above the floating pontoon. The influence of the vessel motions in a seaway introduces large bending moments at the

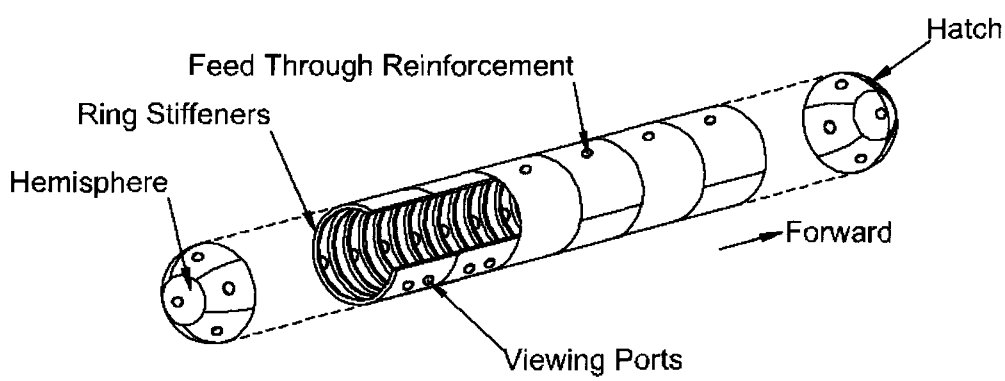

Figure 17.57 Ring-stiffened Submarine Hull

lower end of the legs where they are connected to the pontoon in that condition. This results in a heavy structure at the lower leg ends.

The leg weight and the height of their center of gravity in floating condition thus is the result of structural strength requirements. In turn the required distance between the legs is determined by the requirement that the platform in the elevated condition should not run the risk of overturning due to the influence of the horizontal forces. The hull dimensions are further governed by the afloat stability on which the leg weight and center of gravity have a large impact.

In conclusion it can be seen that the overall design of a jack-up depends in many respects on the structural concept and further structural considerations.

17.11 STRUCTURALAREAS

As shown in the previous section, a large variety of overall structural concepts exist so as each concept can have different local structural concepts, it is clear that the variety therein is still larger. On the other hand, at a still smaller

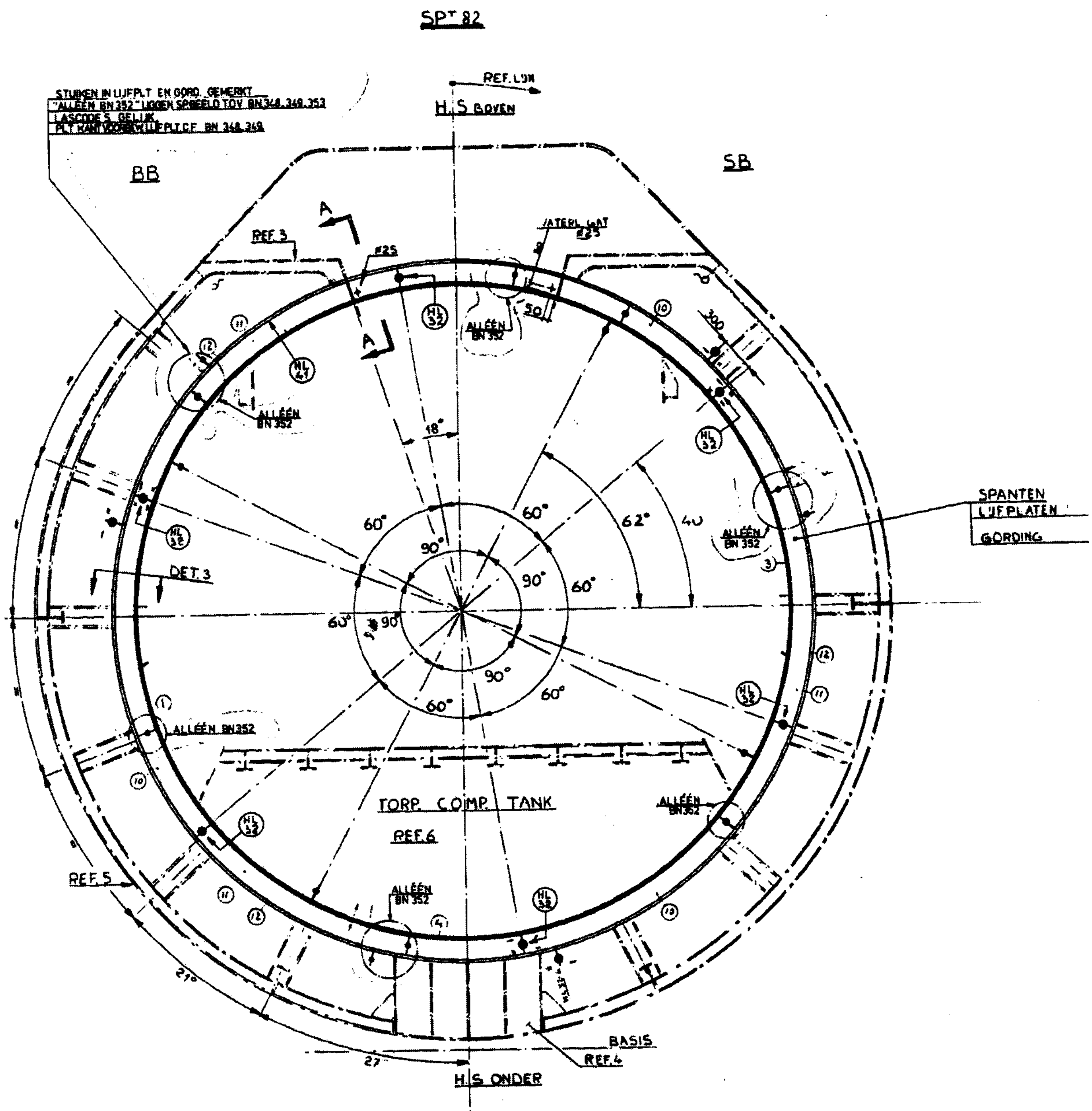

Figure 17.58 Submarine Structural Cross Section

scale similar elements are used over and over again. Orthogonally stiffened plate panels transmitting lateral pressure via the stiffener grid into other plate elements is a structural concept that is used over and over again. This latter level of detailing was considered in section 17.9 - Concepts of Structural Components. The present section deals with the intermediate structural level, that of the structural areas. Much of this is still comparable to what it has been in the past. Yet some general comments on various areas will be made in this section. Some of the comments repeat what has been said in reference 2, others repeat briefly what has been stated earlier in the present chapter and still some others are additional comments drawing attention to some new aspects. The section deals mainly with more traditional mono-hull cargo vessels.

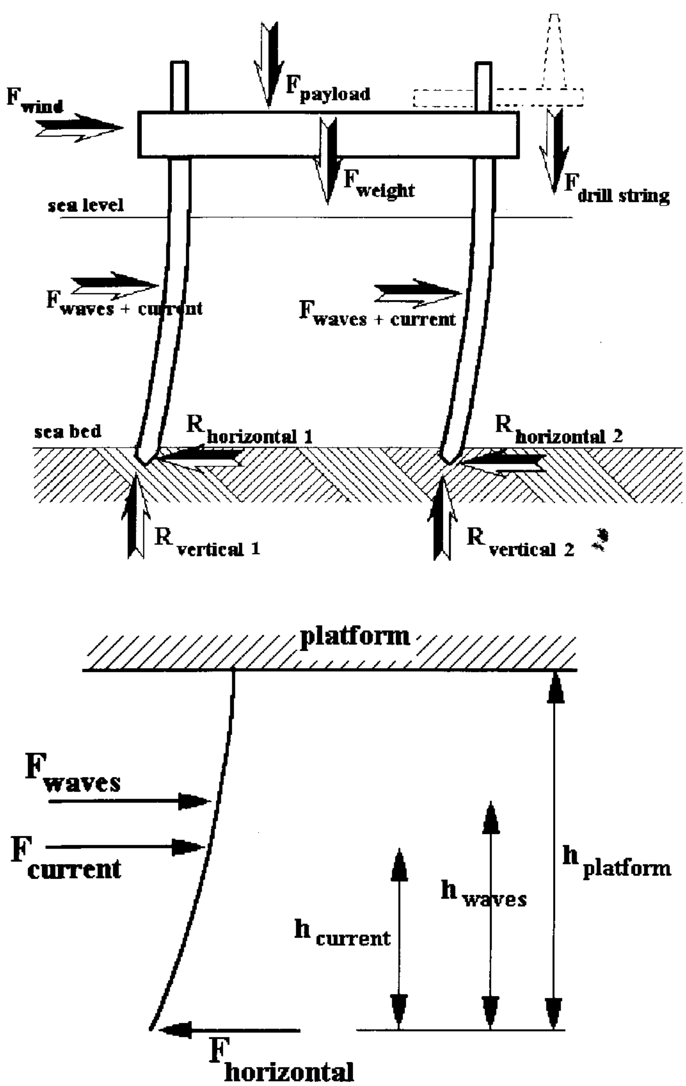

Figure 17.59 Schematic of Loads/Forces on a Jack-up Platform

17.11.1 Midbody

The mid-part of a ship's hull, say between 0.4 and 0.6 L, where L is the ship length, is the most important p'art for providing structural strength. First of all it plays the main role in the overall longitudinal strength of the vessel. The bending moment and the torsional moment normally are maximal in this area. For many ship types the cross section of the hull is open because of large cargo hatches. Vertical shear forces in the vessel hull mostly are not maximum in this area, but just before and after this part. But generally they are less demanding for the vessel structure.

Many advantages and drawbacks of the structure in this part of the ship were discussed in the section on overall structural concepts. The direction of the stiffeners, that is, longitudinal or transverse, is chosen on the basis of fabrication cost, steel weight and sometimes other arguments as mentioned in section 17.10.2.3. The vessel may have one, two or more decks or be an open vessel. Most vessels have double bottoms mainly to facilitate cargo stowage and at the same time provide fuel tank capacity. Some vessels, however, have a single bottom. Many smaller ships, such as fishing vessels, and tugs, have single bottoms because a double bottom would be very small and still require too much costly space and at the same time be relatively expensive to fabricate. Traditionally single bottoms were also provided in tankers and similar ships where cargo stowage is no consideration. Recently also such vessels have a double-bottom in order to reduce the risk of environmental pollution in case of collision and grounding. For a description, see Section 17.10.2.1. Note that structural changes as these may lead to unexpected new problems. Fatigue cracks develop in the bottom plating of double shell tankers around the connection of this plating to the longitudinal stiffeners. This is due to the change in the long-term load distribution on the plate (41). The changes in the connection of the stiffeners to the webs already are mentioned and will be dealt with in Subsection 17.12.2.

Other vessel types often show discontinuities in the midbody area because of stowage and loading arrangements. Typical for this is the side loading port as provided in many short sea traders such as shown in Figure 28.9 in Chapter 28 - Reefer Ships. Their nature leads to stress concentrations often worsened by secondary bending in that area. Together this makes them quite vulnerable to fatigue crack initiation. Careful detail design and analysis is required in such situations.

17.11.2 Machinery Spaces

Machinery spaces in modern ships are mostly located at the aft end of the ships. That position can increase the risk of response to propeller and machinery excitation, resulting in unacceptable vibrations. At the same time the installed power of the engines has significantly increased meaning that the vibration exciting forces have increased. Finally, the acceptance criteria in view of required comfort have become stricter. All of this means that the structure of the machinery spaces must be designed having vibration prevention as a higher objective than previously.

17.11.3 Fore End

The high speed of many modem vessels has led to quite sharp underwater shapes of their bows. Container vessels often have wide decks at the forward end in order to maximize the number of containers. This means that extreme flares may be provided. Severe bow flare slamming with both vertical and horizontal forces may be the consequence. Deck buckling, tension forces on the pillars and shear and compression buckling of the shell plating in container ships and high speed ferries have resulted. Those aspects must be taken into account during the structural design of the fore ship.

On the other hand, wave slapping against the bluff bows of many very large, and thus wide, tankers, bulk carriers and floating production vessels, led to severe damage when these vessels had traditional bow structures. One reason for the damage was that continuation of transverse framing when the shell direction was getting much more transverse resulted in large unsupported spans of the shell plating. At the same time the bow shape made the wave slam pressures higher than for more traditional vessel dimensions. Green water impact on the deck of such vessel types is another additional design criterion. Figure 17.60 shows the typical structure at the fore end of a ship.

17.11.4 Aft End

The structure of the aft end of modem vessels is much influenced by the increased power to be developed by the single propeller. The fine lines of the aft ship may mean that the support around the propeller shaft may be limited in the transverse direction leading to additional vibrations. Cruise liners and some other ship types may show a very wide near-horizontal shell area just above the propeller. This may lead to large impact forces from wave slamming at the aft end. As in the fore ship the deck may be very wide in ship types such as container vessels or ships with a helicopter deck. Special care must be taken to attach such large overhangs securely to the remaining ship structure. Figure 17.61 shows the typical structure at the aft end of a ship.

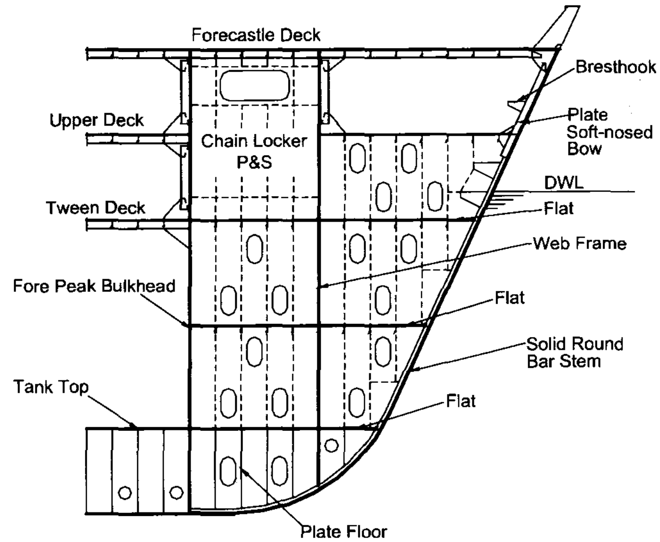

Figure 17.60 Typical Fore End Structural Arrangement

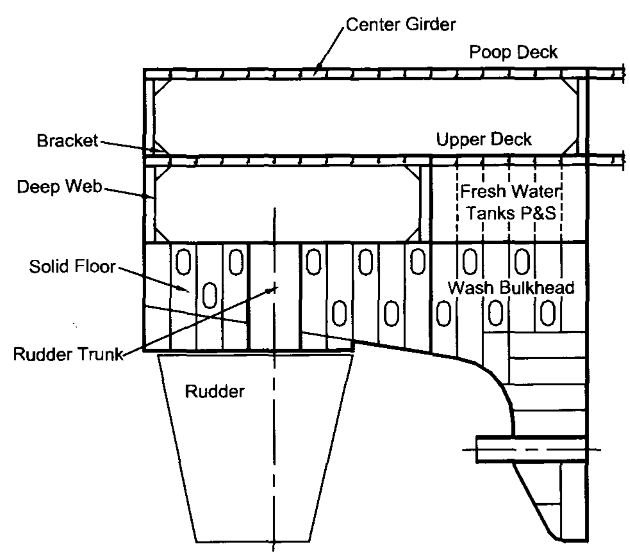

Figure 17.61 Typical Single-screw Stern Structural Arrangement

17.11.5 Superstructure and Oeckhouses

The location of the accommodation block, be it as deckhouses or as superstructure, has moved aft together with the engine room. In container vessels the length of the deckhouse has been reduced as much as possible in order to increase the container storage capacity. This led to high deckhouses with rather small stiffness in the longitudinal direction. The height and low stiffness together with the location at the extreme stem of the ship (because of engine and propeller excitation forces) makes such deckhouses vulnerable to vibrations. Prevention of vibrations has become a major design consideration.

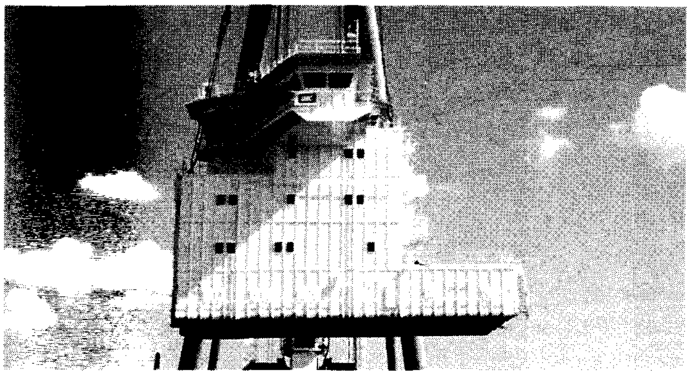

Figure 17.62 Swedged Deckhouse Exterior Bulkheads

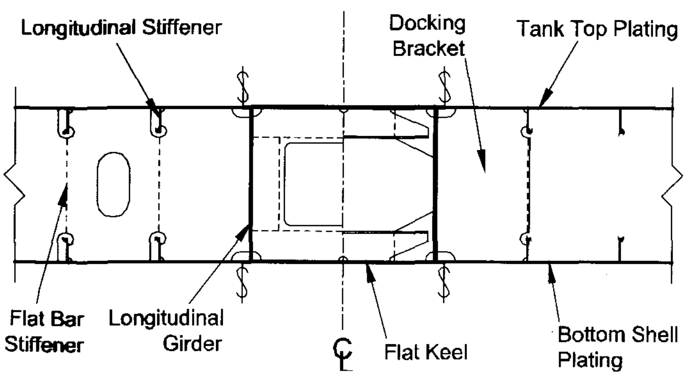

Figure 17.63 Typical Duct-keel Arrangement

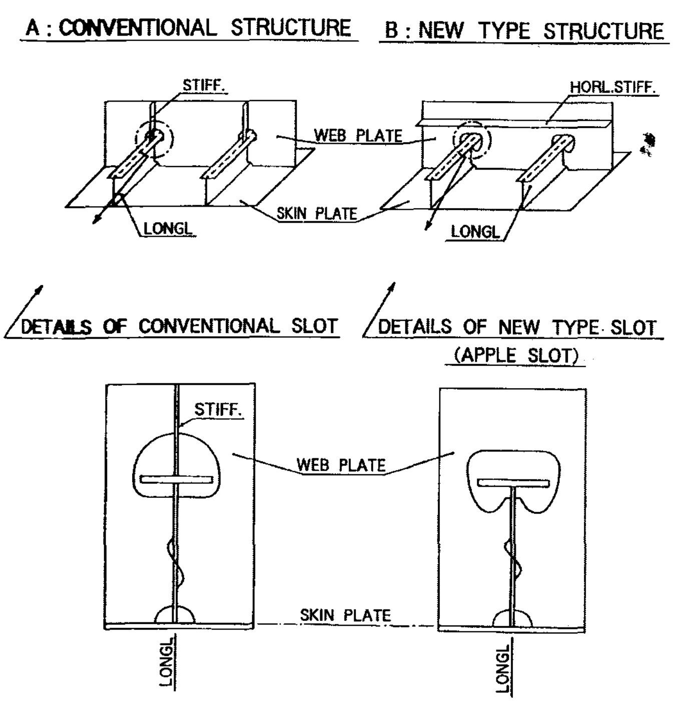

Figure 17.64 Apple Slot Connection

There is a tendency is to make the structure of deckhouses and superstructures, other than those of cruise ships and luxury yachts, cheaper in fabrication costs and lighter in weight. The first goal leads to the use of swedges (folds pressed into the plate) as stiffeners of the plate panels. Swedges are cheap because fewer parts and less welding are needed. At the same time they may have some beneficial effect to the total thickness of wall (plate plus stiffeners) compared to the traditional plate stiffened by rolled profiles. The use of swedges for the external deckhouse walls is considered by some entities not to improve the beauty of the structure (Figure 17.62). The second goal is achieved by use oflighter materials such as aluminum sandwich panels. Noise and vibration reduction may be an added advantage of the use of these materials.

17.12 STRUCTURAL DETAILS EXAMPLES

As previously mentioned several times, there is a nearly infinite variation in ship structures and components. This section describes just a small number of the many examples that could have been chosen. They are presented only to further illustrate some aspects of the present chapter.

17.12.1 Duct-keel

Many ships incorporate a *duct-keel* into the double-bottom arrangement design. It can be used for piping, valves, control piping/cables, access if large enough, etc. Figure 17.63 shows the typical duct-keel structural arrangement.

17.12.2 Web-longitudinal Intersection

Previous sections mentioned the problems that arose in the longitudinal-web intersections of large bulk carriers and tankers. Asymmetric stiffeners and the use of high tensile strength steels have been major contributing factors. Solutions have been sought not only for those aspects, but also the structural concept of the intersection itself offers the potential for improvement.

The so-called *apple slot* is shown in Figure 17.64 compared to the more traditional detail. Note that the conventional detail did not use separate chocks but a close-fitting slot. An important cause of secondary bending in the traditional detail, because of asymmetry of the load and response, thus was eliminated.

The new concept involves load transfer only via the attachment of the transverse web to the web of the longitudinal and omitting the stiffener on top of the longitudinal. By doing so, a main initiation point for fatigue cracking (that is, the weld on top of the longitudinal at a point where high bending stresses occur) has been removed. Secondly, the shape of the slot around the faceplate of the longitudinal has been optimized in shape in view of reducing local stress concentrations at the edge of that opening.

The two measures together resulted in a marked improvement of the fatigue life of this detail. Note that the conceptual change involved two aspects: removing a crack initiation point, and optimizing a shape for reduction of stress concentration. After these conceptual decisions have been taken, the actual application is made possible by the detailed analysis that the finite element technique allows.

17.12.3 Slit Connection

Crossing plates are an essential and often unavoidable detail in all ship structures. This involves the risk of misalignment as discussed in section 17.9.10. One way to overcome this risk is the so-called *egg crate* structure or the *slit connection* as shown in Figure 17.65. The detail, often used on smaller ships, always means interruption of one of the two plates. Preference will be given to that plate where either the stresses perpendicular to the crossing are lowest

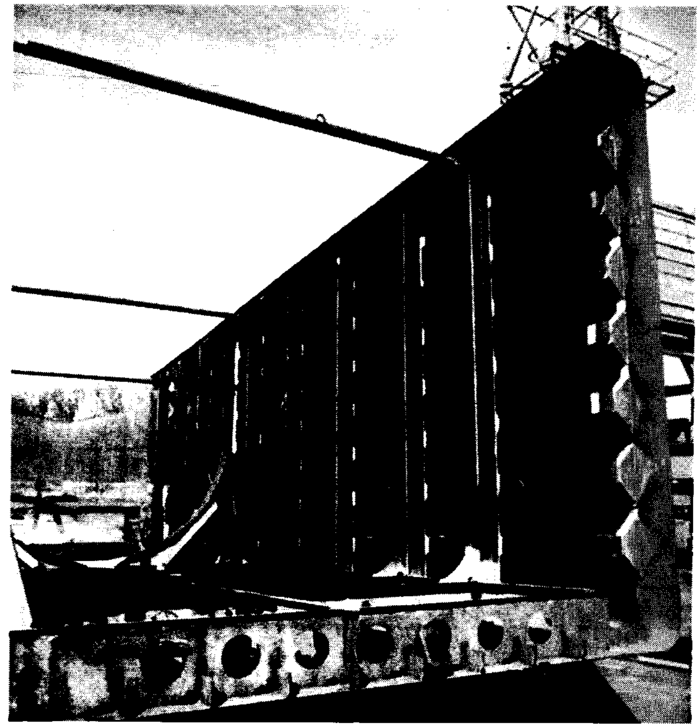

Figure 17.66 River Barge with Collision-resistant Side Structure Under Construction

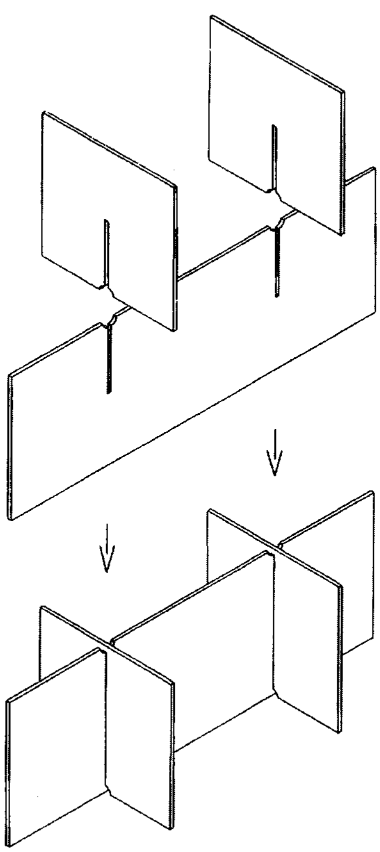

Figure 17.65 Slit Assembly Method

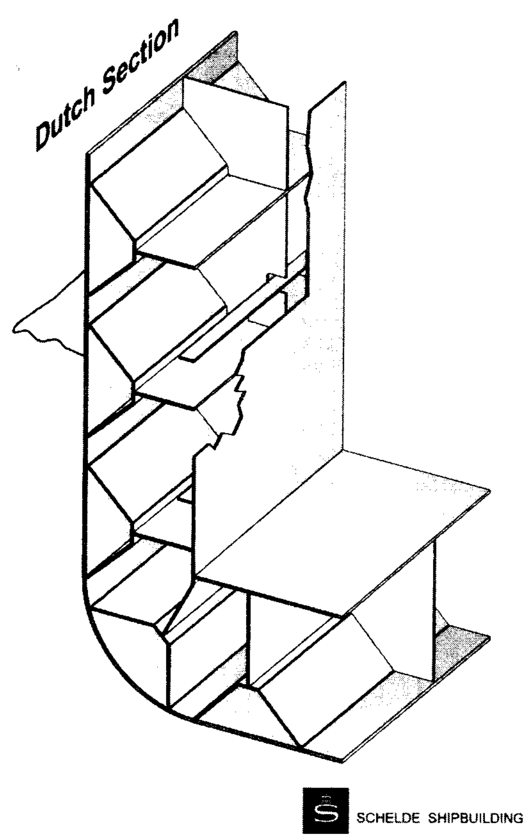

Figure 17.67 Collision Resistant Side Shell Principle

or where a possible crack will have least consequences. Interesting in the detail is that due to the flexibility built in at the non-continuous plate compared to the continuous plate, the stress concentration around the point where the two slits meet is less than intuitively might be expected.

17.12.4 Collision-resistant Side Shell

The present chapter dealt mainly with intact structures. More and more the behavior of the structure after failure is becoming of interest. First of all this concerns the structural reliability once failure of an individual member has occurred. This is a basic feature of the Reliability Based Design as presented in Chapter 19. Much attention has been paid in recent years to the behavior after collision and grounding, in particular of tankers (because of the environment) and ferries (risk for human lives). But also some attention has been given to reducing the consequences once such initiating events have taken place.

Figure 17.66 shows a gas push barge for river trade under construction. The barge was provided with a collision resistant side shell, the principle of which is shown in Figure 1.67. The Y-shaped longitudinals and their attachment to the inner shell offer a support that in case of coll1sion will rotate and buckle. From that point on, this offers a soft support for the shell plating. This will than be stretched as a membrane rather than folded around hard spots. Crack initiation thereby is postponed and membrane action of the shell plate increased. This means that much more energy is absorbed by the shell structure before rupture than in a traditional design (43-45).

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Chapter 18

Analysis and Design of Ship Structure

Philippe Riga and Enrico Rizzuto

18.1 NOMENCLATURE

For specific symbols, refer to the definitions contained in the various sections.

ABS	American Bureau of Shipping
BEM	Boundary Element Method
BV	Bureau Veritas
DNV	Det Norske Veritas
FEA	Finite Element Analysis
FEM	Finite Element Method
lACS	International Association of Classification Societies
ISSC	International Ship & Offshore Structures Congress
ISOPE	International Offshore and Polar En~ neering Conference
ISUM	Idealized Structural Unit method
NKK	Nippon Kaiji Kyokai
PRADS	Practical Design of Ships and Mobile Units,
RINA	Registro Italiano Navale
SNAME	Society of naval Architects and marine Engineers
SSC	Ship Structure Committee.
a	acceleration
A	area
B	breadth of the ship
C	wave coefficient (Table 18.!)
C_B	hull block coefficient
D	depth of the ship
g	gravity acceleration
m(x)	longitudinal distribution of mass
I(x)	geometric moment of inertia (beam section x)
L	length of the ship
M(x)	bending moment at section x of a beam
$M_T(x)$	torque moment at section x of a beam
p	pressure
q(x)	resultant of sectional force acting on a beam
T	draft of the ship
V(x)	shear at section x of a beam
$_{s,w}$ (low case)	still water, wave induced component
$_{v,h}$ (low case)	vertical, horizontal component
w(x)	longitudinal distribution of weight
θ	roll angle
ρ	density
ω	angular frequency

18.2 INTRODUCTION

The purpose of this chapter is to present the fundamentals of direct ship structure analysis based on mechanics and strength of materials. Such analysis allows a rationally based design that is practical, efficient, and versatile, and that has already been implemented in a computer program, tested, and proven.

Analysis and *Design* are two words that are very often associated. Sometimes they are used indifferently one for the other even if there are some important differences between performing a design and completing an analysis.

Analysis refers to stress and strength assessment of the structure. Analysis requires information on loads and needs an initial structural scantling design. Output of the structural analysis is the structural response defined in terms of stresses, deflections and strength. Then, the estimated response is compared to the design criteria. Results of this comparison as well as the objective functions (weight, cost, etc.) will show if updated (improved) scantlings are required.

Design for structure refers to the process followed to select the initial structural scantlings and to update these scantlings from the early design stage (bidding) to the detailed design stage (construction). To perform analysis, initial design is needed and analysis is required to design. This explains why design and analysis are intimately linked, but are absolutely different. Of course design also relates to topology and layout definition.

The organization and framework of this chapter are based on the previous edition of the *Ship Design and Construction* (1) and on the Chapter IV of *Principles of Naval Architecture* (2). Standard materials such as beam model, twisting, shear lag, etc. that are still valid in 2002 are partly duplicated from these 2 books. Other major references used to write this chapter are *Ship Structural Design* (3) also published by SNAME and the *DNV 99-0394 Technical Report (4).*

The present chapter is intimately linked with Chapter 11 - Parametric Design, Chapter 17 - Structural Arrangement and Component Design and with Chapter 19 - Reliability-Based Structural Design. References to these chapters will be made in order to avoid duplications. In addition, as Chapter 8 deals with classification societies, the present chapter will focus mainly on the direct analysis methods available to perform a rationally based structural design, even if mention is made to standard formulations from Rules to quantify design loads.

In the following sections of this chapter, steps of a~lobal analysis are presented. Section 18.3 concerns the loads that are necessary to perform a structure analysis. Then, Sections 18.4, 18.5 and 18.6 concern, respectively, the stresses and deflections (basic ship responses), the limit states, and the failures modes and associated structural capacity. A review of the available *Numerical Analysis for Structural Design* is performed in Section 18.7. Finally *Design Criteria* (Section 18.8) and *Design Procedures* (Section 18.9) are discussed. *Structural modeling* is discussed in Subsection 18.2.2 and more extensively in Subsection 18.7.2 for finite element analysis. *Optimization* is treated in Subsections 18.7.6 and 18.9.4.

Ship structural design is a challenging activity. Hence Hughes (3) states:

> The complexities of modern ships and the demand for greater reliability, efficiency, and economy require a scientific, powerful, and versatile method for their structural design.

But, even with the development of numerical techniques, design still remains based on the designer's experience and on previous designs. There are many designs that satisfy the strength criteria, but there is only one that is the optimum solution (least cost, weight, etc.).

Ship structural analysis and design is a matter of compromIses:

- compromise between accuracy and the available time to perform the design. This is particularly challenging at the preliminary design stage. A 3D Finite Element Method (FEM) analysis would be welcome but the time is not available. For that reason, rule-based design or simplified numerical analysis has to be performed.
- to limit uncertainty and reduce conservatism in design, it is important that the design methods are accurate. On the other hand, simplicity is necessary to make repeated design analyses efficient. The results from complex analyses should be verified by simplified methods to avoid errors and misinterpretation of results (checks and balances).
- compromise between weight and cost,
- compromise between least construction cost, and global owner live cycle cost (including operational cost, maintenance, etc.), and
- builder optimum design is usually different from the owner optimum design.

18.2.1 Rationally Based Structural Design versus Rules-Based Design

There are basically two schools to perform analysis and design of ship structure. The first one, the oldest, is called *rule-based design.* It is mainly based on the rules defined by the classification societies. Hughes (3) states:

> In the past, ship structural design has been largely empirical, based on accumulated experience and ship performance, and expressed in the form of structural design codes or rules published by the various ship classification societies. These rules concern the loads, the strength and the design criteria and provide simplified and easy-to-use formulas for the structural dimensions, or "scantlings" of a ship. This approach saves time in the design office and, since the ship must obtain the approval of a classification society, it also saves time in the approval process.

The second school is the *Rationally Based Structural Design;* it is based on direct analysis. Hughes, who could be considered as a *father* of this methodology, (3) further states:

There are several disadvantages to a completely "rulebook" approach to design. First, the modes of structural failure are numerous, complex, and interdependent. With such simplified formulas the margin against failure remains unknown; thus one cannot distinguish between structural adequacy and over-adequacy. Second, and most important, these formulas involve a number of simplifying assumptions and can be used only within certain limits. Outside of this range they may be inaccurate.

For these reasons there is a general trend toward direct structural analysis.

Even if direct calculation has always been performed, design based on direct analysis only became popular when numerical analysis methods became available and were certified. Direct analysis has become the standard procedure in aerospace, civil engineering and partly in offshore industries. **In** ship design, classification societies preferred to offer updated rules resulting from numerical analysis calibration. For the designer, even if the rules were continuously changing, the design remained *rule-based.* There really were two different methodologies.

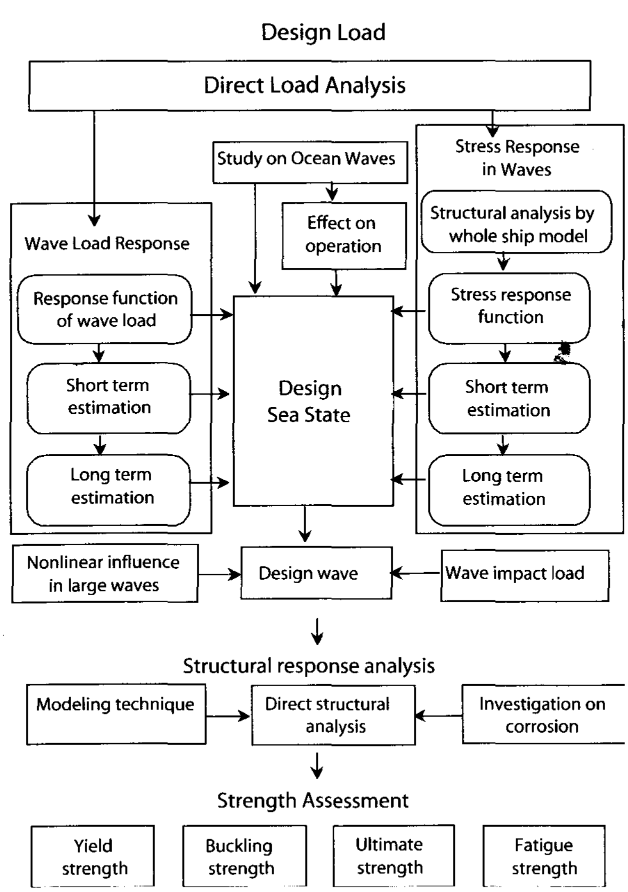

Figure 18.1 Direct Structural Analysis Flow Chart

Hopefully, in 2003 this is no longer true. The advantages of direct analysis are so obvious that classification societies include, usually as an alternative, a direct analysis prQcedure (numerical packages based on the finite element method, see Table 18.VIII, Subsection 18.7.5.1). **In** addition, fornew vessel types or non-standard dimension, such direct procedure is the only way to assess the structural safety. Therefore it seems that the two schools have started a long merging procedure. Classification societies are now encouraging and contributing greatly to the development of direct analysis and rationally based methods. Ships are very complex structures compared with other types of structures. They are subject to a very wide range of loads in the harsh environment of the sea. Progress in technologies related to ship design and construction is being made daily, at an unprecedented pace. A notable example is the fact that the efforts of a majority of specialists together with rapid advances in computer and software technology have now made it possible to analyze complex ship structures in a practical manner using structural analysis techniques centering on FEM analysis. The majority of ship designers strive to develop rational and optimal designs based on direct strength analysis methods using the latest technologies in order to realize the shipowner's requirements in the best possible way.

When carrying out direct strength analysis to verify the equivalence of structural strength with rule requirements, it is necessary for the classification society to clarify the strength that a **hull** structure should have with respect to each ofthe various steps taken in the analysis process, from load estimation through to strength evaluation. **In** addition, in order to make this a practical and effective method of analysis, it is necessary to give careful consideration to more rational and accurate methods of direct strength analysis.

Based on recognition of this need, extensive research has been conducted and a careful examination made, regarding the strength evaluation of **hull** structures. The results of this work have been presented in papers and reports regarding direct strength evaluation of hull structures (4,5).

The flow chart given in Figure 18.1 gives an overview of the analysis as defined by a major classification society.

Note that a rationally based design procedure requires that all design decisions (objectives, criteria, priorities, constraints ...) must be made before the design starts. This is a major difficulty of this approach.

18.2.2 Modeling and Analysis

General guidance on the modeling necessary for the structural analysis is that the structural model shall provide results suitable for performing buckling, yield, fatigue and vibration assessment of the relevant parts of the vessel. This

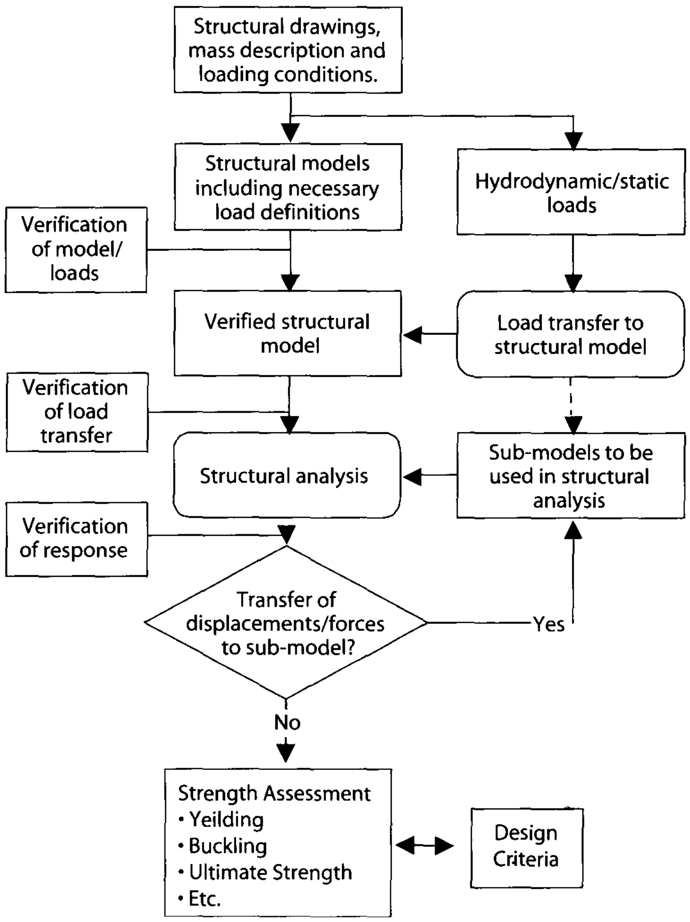

Figure 18.2 Strength Analysis Flow Chart (4)

is done by using a 3D model of the whole ship, supported by one or more levels of sub models.

Several approaches may be applied such as a detailed 3D model of the entire ship or coarse meshed 3D model supported by finer meshed sub models.

Coarse mesh can be used for determining stress results suited for yielding and buckling control but also to obtain the displacements to apply as boundary conditions for sub models with the purpose of determining the stress level in more detail (for fatigue).

Strength analysis covers yield (allowable stress), buckling strength and ultimate strength checks of the ship. In addition, specific analyses are requested for fatigue (Subsection 18.6.6), collision and grounding (Subsection 18.6.7) and vibration (Subsection 18.6.8). The hydrodynamic load model must give a good representation of the wetted surface of the ship, both with respect to geometry description and with respect to hydrodynamic requirements. The mass model, which is part of the hydrodynamic load model, must ensure a proper description of local and global moments of inertia around the global ship axes.

Ultimate hydrodynamic loads from the hydrodynamic analysis should be combined with static loads in order to form the basis for the yield, buckling and ultimate strength checks. All the relevant load conditions should be examined to ensure that all dimensioning loads are correctly included. A flow chart of strength analysis of global model and sub models is shown in Figure 18.2.

18.2.3 Preliminary Design versus Detailed Design

For a ship structure, structural design consists of two distinct levels: the *Preliminary Design* and the *Detailed Design* about which Hughes (3) states:

> The preliminary design determines the location, spacing, and scantlings of the principal structural members. The detailed design determines the geometry and scantlings oflocal structure (brackets, connections, cutouts, reinforcements, etc.).
>
> Preliminary design has the greatest influence on the structure design and hence is the phase that offers very large potential savings. This does not mean that detail design is less important than preliminary design. Each level is equally important for obtaining an efficient, safe and reliable ship.
>
> During the detailed design there also are many benefits to be gained by applying modem methods of engineering science, but the applications are different from preliminary design and the benefits are likewise different.
>
> Since the items being designed are much smaller it is possible to perform full-scale testing, and since they are more repetitive it is possible to obtain the benefits of mass production, standardization and so on. In fact, production aspects are of primary importance in detail design.
>
> Also, most of the structural items that come under detail design are similar from ship to ship. and so in-service experience provides a sound basis for their design. In fact, because of the large number of such items it would be inefficient to attempt to design all of them from first principles. Instead it is generally more efficient to use design codes and standard designs that have been proven by experience. In other words, detail design is an area where a rule-based approach is very appropriate, and the rules that are published by the various ship classification societies contain a great deal of useful information on the design of local structure, structural connections, and other structural details.

18.3 LOADS

Loads acting on a ship structure are quite varied and peculiar, in comparison to those of static structures and also of other vehicles. In the following an attempt will be made to review the main typologies of loads: physical origins, general interpretation schemes, available quantification procedures and practical methods for their evaluation will be summarized.

18.3.1 Classification of Loads

18.3.1.1 Time Duration

Static loads: These are the loads experienced by the ship in still water. They act with time duration well above the range of sea wave periods. Being related to a specific load condition, they have little and very slow variations during a voyage (mainly due to changes in the distribution of consumables on board) and they vary significantly only during loading and unloading operations.

Quasi-static loads: A second class of loads includes those with a period corresponding to wave actions (-3 to 15 seconds). Falling in this category are loads directly induced by waves, but also those generated in the same frequency range by motions of the ship (inertial forces). These loads can be termed quasi-static because the structural response is studied with static models.

Dynamic loads: When studying responses with frequency components close to the first structural resonance modes, the dynamic properties of the structure have to be considered. This applies to a few types of periodic loads, generated by wave actions in particular situations (springing) or by mechanical excitation (main engine, propeller). Also transient impulsive loads that excite free structural vibrations (slamming, and in some cases sloshing loads) can be classified in the same category.

Highfrequency loads: Loads at frequencies higher than the first resonance modes (> 10-20 Hz) also are present on ships: this kind of excitation, however, involves more the study of noise propagation on board than structu,.l design.

Other loads: All other loads that do not fall in the above mentioned categories and need specific models can be generally grouped in this class. Among them are thermal and accidental loads.

A large part of ship design is performed on the basis of static and quasi-static loads, whose prediction procedures are quite well established, having been investigated for a long time. However, specific and imposing requirements can arise for particular ships due to the other load categones.

18.3.1.2 Local and global loads

Another traditional classification of loads is based on the structural scheme adopted to study the response.

Loads acting on the ship as a whole, considered as a beam (hull girder), are named global or primary loads and the ship structural response is accordingly termed global or primary response (see Subsection 18.4.3).

Loads, defined in order to be applied to limited structural models (stiffened panels, single beams, plate panels), generally are termed local loads.

The distinction is purely formal, as the same external forces can in fact be interpreted as global or local loads. For instance, wave dynamic actions on a portion of the hull, if described in terms of a bi-dimensional distribution of pressures over the wet surface, represent a local load for the hull panel, while, if integrated over the same surface, represent a contribution to the bending moment acting on the hull girder.

This terminology is typical of simplified structural analyses, in which responses of the two classes of components are evaluated separately and later summed up to provide the total stress in selected positions of the structure.

In a complete 3D model of the whole ship, forces on the structure are applied directly in their actual position and the result is a total stress distribution, which does not need to be decomposed.

18.3.1.3 Characteristic values for loads

Structural verifications are always based on a limit state equation and on a design operational time.

Main aspects of reliability-based structural design and analysis are (see Chapter 19):

- the state of the structure is identified by state variables associated to loads and structural capacity,
- state variables are stochastically distributed as a function of time, and
- the probability of exceeding the limit state surface in the design time (probability of crisis) is the element subject to evaluation.

The situation to be considered is in principle the worst combination of state variables that occurs within the design time. The probability that such situation corresponds to an out crossing of the limit state surface is compared to a (low) target probability to assess the safety of the structure.

This general time-variant problem is simplified into a time-invariant one. This is done by taking into account in the analysis the worst situations as regards loads, and, separately, as regards capacity (reduced because of corrosion and other degradation effects). The simplification lies in considering these two situations as contemporary, which in general is not the case.

When dealing with strength analysis, the worst load situation corresponds to the highest load cycle and is characterized through the probability associated to the extreme value in the reference (design) time.

In fatigue phenomena, in principle all stress cycles contribute (to a different extent, depending on the range) to damage accumulation. The analysis, therefore, does not regard the magnitude of a single extreme load application, but the number of cycles and the shape of the probability distribution of all stress ranges in the design time.

A further step towards the problem simplification is represented by the adoption of characteristic load values in place of statistical distributions. This usually is done, for example, when calibrating a Partial Safety Factor format for structural checks. Such adoption implies the definition of a single reference load value as representative of a whole probability distribution. This step is often performed by assigning an *exceeding probability* (or a *return period)* to each variable and selecting the correspondent value from the statistical distribution.

The *exceeding probability* for a stochastic variable has the meaning of probability for the variable to overcome a given value, while the *return period* indicates the mean time to the first occurrence.

Characteristic values for ultimate state analysis are typically represented by loads associated to an exceeding probability of 10^{-8}. This corresponds to a wave load occurring, on the average, once every 10^8 cycles, that is, with a return period of the same order of the ship lifetime. In first yielding analyses, characteristic loads are associated to a higher exceeding probability, usually in the range 10^{-4} to 10^{-6}. In fatigue analyses (see Subsection 18.6.6.2), reference loads are often set with an exceeding probability in the range 10^{-3} to 10^{-5}, corresponding to load cycles which, by effect of both amplitude and frequency of occurrence, contribute more to the accumulation of fatigue damage in the structure.

On the basis ofthis, all design loads for structural analyses are explicitly or implicitly related to a low exceeding probability.

18.3.2 Definition of Global Hull Girder Loads

The global structural response of the ship is studied with reference to a beam scheme (hull girder), that is, a monodimensional structural element with sectional characteristics distributed along a longitudinal axis.

Actions on the beam are described, as usual with this scheme, only in terms of forces and moments acting in the transverse sections and applied on the longitudinal axis.

Three components act on each section (Figure 18.3): a resultant force along the vertical axis of the section (contained in the plane of symmetry), indicated as vertical resultant force q_V; another force in the normal direction, Oocal horizontal axis), termed horizontal resultant force q_H and a moment m_T about the x axis. All these actions are distributed along the longitudinal axis x.

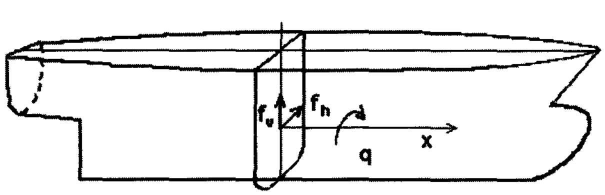

Figure 18.3 Sectional Forces and Moment

Five main load components are accordingly generated along the beam, related to sectional forces and moment through equation 1 to 5:

$$V_V(x) = \int_0^x q_V(\xi)\, d\xi \qquad [1]$$

$$M_V(x) = \int_0^x V_V(\xi)\, d\xi \qquad [2]$$

$$V_H(x) = \int_0^x q_H(\xi)\, d\xi \qquad [3]$$

$$M_H(x) = \int_0^x V_H(\xi)\, d\xi \qquad [4]$$

$$M_T(x) = \int_0^x m_T(\xi)\, d\xi \qquad [5]$$

Due to total equilibrium, for a beam in free-free conditions (no constraints at ends) all load characteristics have zero values at ends (equations 6).

These conditions impose constraints on the distributions of q_V, q_H and m_T.

$$\begin{aligned} &V_V(0) = V_V(L) = M_V(0) = M_V(L) = 0 \\ &V_H(0) = V_H(L) = M_H(0) = M_H(L) = 0 \qquad [6] \\ &M_T(0) = M_T(L) = 0 \end{aligned}$$

Global loads for the verification of the hull girder are obtained with a linear superimposition of still water and wave-induced global loads.

They are used, with different characteristic values, in different types of analyses, such as ultimate state, first yielding, and fatigue.

18.3.3 Still Water Global Loads

Still water loads act on the ship floating in calm water, usually with the plane of symmetry normal to the still water surface. In this condition, only a symmetric distribution of hydrostatic pressure acts on each section, together with vertical gravitational forces.

If the latter ones are not symmetric, a sectional torque mTlx) is generated (Figure 18.4), in addition to the verticalload qsv(x), obtained as a difference between buoyancy b(x) and weight w(x), as shown in equation 7 (2).

$$q_{SV}(x) = b(x) - w(x) = gA_I(x) - m(x)g \qquad [7]$$

where AI = transversal immersed area.

Components of vertical shear and vertical bending can be derived according to equations 1 and 2. There are no horizontal components of sectional forces in equation 3 and accordingly no components of horizontal shear and bending moment. As regards equation 5, only m_{Tg}, if present, is to be accounted for, to obtain the torque.

18.3.3.1 Standard still water bending moments

While buoyancy distribution is known from an early stage of the ship design, weight distribution is completely defined only at the end of construction. Statistical formulations, calibrated on similar ships, are often used in the design development to provide an approximate quantification of weight items and their longitudinal distribution on board. The resulting approximated weight distribution, together with the buoyancy distribution, allows computing shear and bending moment.

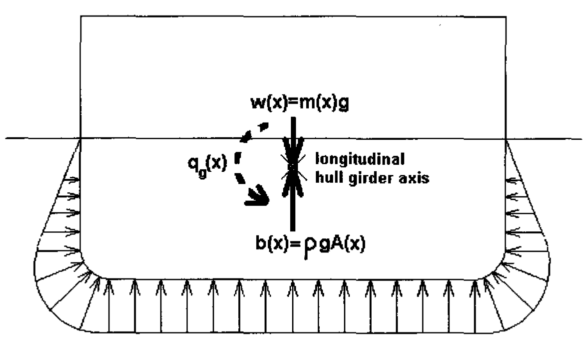

Figure 18.4 Sectional Resultant Forces in Still Water

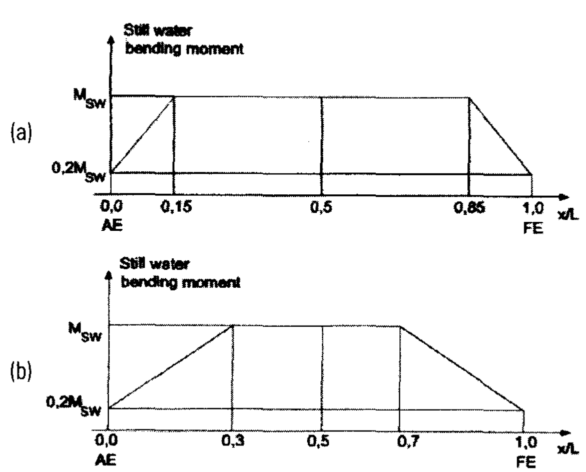

Figure 18.5 Examples of Reference Still Water Bending Moment Distribution (10). (a) oil tankers, bulk carriers, ore carriers, and (b) other ship types

At an even earlier stage of design, parametric formulations can be used to derive directly reference values for still water hull girder loads.

Common reference values for still water bending moment at mid-ship are provided by the major Classification Societies (equation 8).

$$M_S[N \cdot m] = \begin{matrix} C\ L^2\ B\left(122.5 - 15\, C_B\right)\ \text{(hogging)} \\ C\ L^2\ B\left(45.5 + 65\, C_B\right)\ \text{(sagging)} \end{matrix} \qquad [8]$$

where C = wave parameter (Table 18.1).

The formulations in equation 8 are sometimes explicitly reported in Rules, but they can anyway be indirectly derived from prescriptions contained in (6, 7). The first requirement (6) regards the minimum longitudinal strength modulus and provides implicitly a value for the total bending moment; the second one (7), regards the wave induced component of bending moment.

Longitudinal distributions, depending on the ship type, are provided also. They can slightly differ among Class Societies, (Figure 18.5).

18.3.3.2 Direct evaluation of still water global loads

Classification Societies require in general a direct analysis of these types of load in the main loading conditions of the ship, such as homogenous loading condition at maximum draft, ballast conditions, docking conditions afloat, plus all other conditions that are relevant to the specific ship (non-homogeneous loading at maximum draft, light load at less than maximum draft, short voyage or harbor condition, ballast exchange at sea, etc.).

The direct evaluation procedure requires, for a given loading condition, a derivation, section by section, of vertical resultants of gravitational (weight) and buoyancy forces, applied along the longitudinal axis *x* of the beam.

To obtain the weight distribution w(x), the ship length is subdivided into portions: for each of them, the total weight and center of gravity is determined summing up contributions from all items present on board between the two bounding sections. The distribution for w(x) is then usually approximated by a linear (trapezoidal) curve obtained by imposing

TABLE 18.1 Wave Coefficient Versus Length

Ship Length L	*Wave Coefficient C*
$90 \le L < 300$ m	$10.75 - [(300 - L)/100]^{3/2}$
$300 \le L < 350$ m	10.75
$350 \le L$	$10.75 - [(300 - L)/150]^{3/2}$

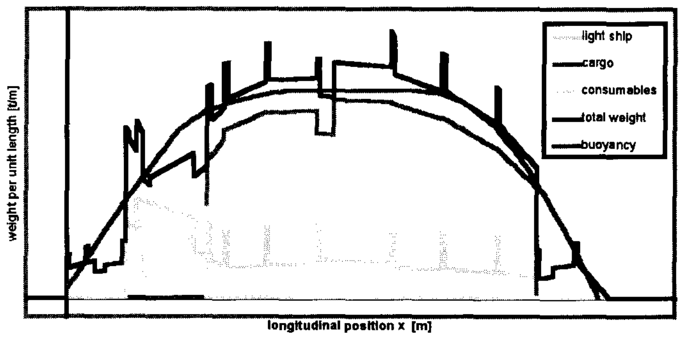

Figure 18.6 Weight Distribution Breakdown for Full Load Condition

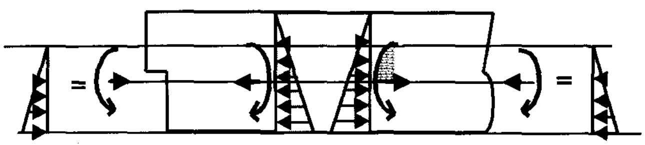

Figure 18.7 Longitudinal Component of Pressure

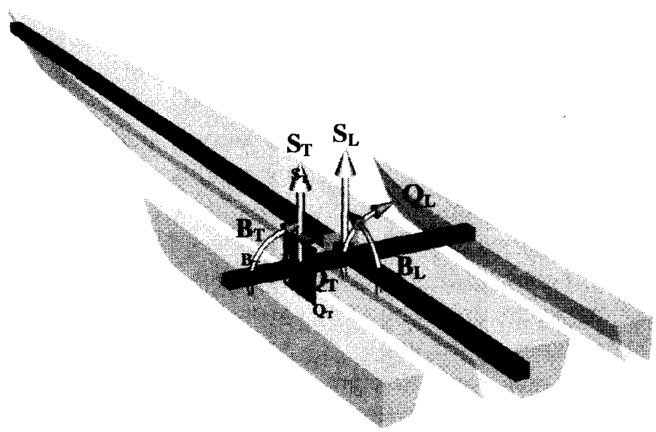

Figure 18.8 Multi-hull Additional Still Water Loads (sketch)

the correspondence of area and barycenter of the trapezoid respectively to the total weight and center of gravity of the considered ship portion.

The procedure is usually applied separately for different types of weight items, grouping together the weights of the ship in lightweight conditions (always present on board) and those (cargo, ballast, consumables) typical of a loading condition (Figure 18.6).

18.3.3.3 Uncertainties in the evaluation

A significant contribution to uncertainties in the evaluation of still water loads comes from the inputs to the procedure, in particular those related to quantification and location on board of weight items.

This lack of precision regards the weight distribution for the ship in lightweight condition (hull structure, machinery, outfitting) but also the distribution of the various components of the deadweight (cargo, ballast, consumables).

Ship types like bulk carriers are more exposed to uncertainties on the actual distribution of cargo weight than, for example, container ships, where actual weights of single containers are kept under close control during operation.

In addition, model uncertainties arise from neglecting the longitudinal components of the hydrostatic pressure (Figure 18.7), which generate an axial compressive force on the hull girder.

As the resultant of such components is generally below the neutral axis of the hull girder, it leads also to an additional hogging moment, which can reach up to 10% of the total bending moment. On the other hand, in some vessels (in particular tankers) such action can be locally counterbalanced by internal axial pressures, causing hull sagging moments.

All these compression and bending effects are neglected in the hull beam model, which accounts only for forces and moments acting in the transverse plane. This represents a source of uncertainties.

Another approximation is represented by the fact that buoyancy and weight are assumed in a direction normal to the horizontal longitudinal axis, while they are actually oriented along the true vertical.

This implies neglecting the static trim angle and to consider an approximate equilibrium position, which often creates the need for a few iterative corrections to the load curve qs/x) in order to satisfy boundary conditions at ends (equations 6).

18.3.3.4 Other still water global loads

In a vessel with a multihull configuration, in addition to conventional still water loads acting on each hull considered as a single longitudinal beam, also loads in the transversal direction can be significant, giving rise to shear, bending and torque in a transversal direction (see the simplified scheme of Figure 18.8, where S, B, and Q stand for shear, bending and torque; and L, T apply respectively to longitudinal and transversal beams).

18.3.4 Wave Induced Global Loads

The prediction of the behaviour of the ship in waves represents a key point in the quantification of both global and local loads acting on the ship. The solution of the seakeeping problem yields the loads directly generated by external pressures, but also provides ship motions and accelerations. The latter are directly connected to the quantification of inertialloads and provide inputs for the evaluation of other types of loads, like slamming and sloshing.

In particular, as regards global effects, the action of waves modifies the pressure distribution along the wet hull surface; the differential pressure between the situation in waves and in still water generates, on the transverse section, vertical and horizontal resultant forces (b_{WV} and b_{WH}) and a moment component m_{Th}.

Analogous components come from the sectional resultants of inertial forces and moments induced on the section by ship's motions (Figure 18.9).

The total vertical and horizontal wave induced forces on the section, as well as the total torsional component, are found summing up the components in the same direction (equations 9).

$$\begin{aligned} q_{WV}(x) &= b_{WV}(x) - m(x)a_V(x) \\ q_{WH}(x) &= b_{WH}(x) - m(x)a_H(x) \\ m_{TW}(x) &= m_{Tb}(x) - I_R(x)\,\theta \end{aligned} \quad [9]$$

where IR(x) is the rotational inertia of section *x*.

The longitudinal distributions along the hull girder of horizontal and vertical components of shear, bending moment and torque can then be derived by integration (equations I to 5).

Such results are in principle obtained for each instantaneous wave pressure distribution, depending therefore, on time, on type and direction of sea encountered and on the ship geometrical and operational characteristics.

In regular (sinusoidal) waves, vertical bending moments tend to be maximized in head waves with length close to the ship length, while horizontal bending and torque components are larger for oblique wave systems.

18.3.4.1 Statistical formulae for global wave loads

Simplified, first approximation, formulations are available for the main wave load components, developed mlnly on the basis of past experience.

Vertical wave-induced bending moment: lACS classification societies provide a statistically based reference values for the vertical component of wave-induced bending moment *Mwv,* expressed as a function of main ship dimensions.

Such reference values for the midlength section of a ship with unrestricted navigation are yielded by equation 10 for hog and sag cases (7) and corresponds to an extreme value with a return period of about 20 years or an exceeding probability of about 10^{-8} (once in the ship lifetime).

$$M_{WV}\,[N\cdot m] = \begin{array}{ll} 190\ C\,L^2\ B\,C_B & \text{(hog)} \\ -110\ C\ L^2\ B\left(C_B + 0.7\right) & \text{(sag)} \end{array} \quad [10]$$

Horizontal Wave-induced Bending Moment: Similar formulations are available for reference values of horizontal wave induced bending moment, even though they are not as uniform among different Societies as for the main vertical component.

In Table 18.II, examples are reported of reference values of horizontal bending moment at mid-length for ships with unrestricted navigation. Simplified curves for the distribution in the longitudinal direction are also provided.

Wave-induced Torque: A few reference formulations are given also for reference wave torque at midship (see examples in Table 18.III) and for the inherent longitudinal distributions.

18.3.4.2 Static wave analysis of global wave loads

A traditional analysis adopted in the past for evaluation of wave-induced loads was represented by a quasi-static wave approach. The ship is positioned on *afreezed* wave of given characteristics in a condition of equilibrium between weight and static buoyancy. The scheme is analogous to the one described for still water loads, with the difference that the waterline upper boundary of the immersed part of the hull is no longer a plane but it is a curved (cylindrical) surface. By definition, this procedure neglects all types of dynamic effects. Due to its limitations, it is rarely used to quantify wave loads. Sometimes, however, the concept of *equivalent static wave* is adopted to associate a longitudinal distribution of

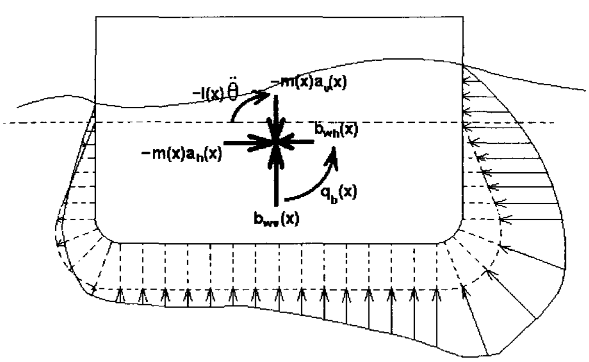

Figure 18.9 Sectional Forces and Moments in Waves

TABLE 18.II Reference Horizontal Bending Moments

Class Society	$M_{WH}\,[N\cdot m]$
ABS (8)	$180\ C_1L^2DC_B$
BV (9) RINA (10)	$1600\ L^{2.1}\ TC_B$
DNV (11)	$220\ L^{9/4}(T + 0.3B)C_B$
NKK (12)	$320\ L_2C\ \ T\sqrt{L - 35 / L}$

TABLE 18.III Examples of Reference Values for Wave Torque

Class Society	Q_w *[N · m] (at mid-ship)*
ABS (bulk carrier)	$2700LB^2T\left[(C_W-0.5)^2+0.1\right]\left[0.13-\frac{e}{D}\left(\frac{0.14}{T}\right)^{0.5}\right]$ (e = vertical position of shear center)
BV RINA	$190LB^2C_W^2\left[8.13-\left(\frac{250-0.7L}{125}\right)^3\right]$

pressures to extreme wave loads, derived, for example, from long term predictions based on other methods.

18.3.4.3 Linear methods for wave loads

The most popular approach to the evaluation of wave loads is represented by solutions of a linearized potential flow problem based on the so-called *strip theory* in the frequency domain (13).

The theoretical background of this class of procedures is discussed in detail in PNA Vol. III (2).

Here only the key assumptions of the method are presented:

- *inviscid, incompressible and homogeneous fluid in irrotational flow:* Laplace equation 11

$$\nabla^2\Phi = 0 \qquad [11]$$

where Φ = velocity potential

- 2-dimensional solution of the problem
- *linearized boundary conditions:* the quadratic component of velocity in the Bernoulli Equation is reformulated in linear terms to express boundary conditions:
  - *on free surface*: considered as a plane corresponding to still water: fluid velocity normal to the free surface equal to velocity of the surface itself (kinematic condition); zero pressure,
  - *on the hull*: considered as a static surface, corresponding to the mean position of the hull: the component of the fluid velocity normal to the hull surface is zero (impermeability condition), and
- *linear decomposition* into additive independent components, separately solved for and later summed up (equation 12).

$$\Phi = \Phi_s + \Phi_{FK} + \Phi_d + \Phi_r \qquad [12]$$

where:

Φ_s = stationary component due to ship advancing in calm water

Φ_r = radiation component due to the ship motions in calm water

Φ_{FK} = excitation component, due to the incident wave (undisturbed by the presence of the ship): Froude-Krylov

Φ_d = diffraction component, due to disturbance in the wave potential generated by the hull

This subdivision also enables the de-coupling of the excitation components from the response ones, thus avoiding a non-linear feedback between the two.

Other key properties of linear systems that are used in the analysis are:

- linear relation between the input and output amplitudes, and
- superposition of effects (sum of inputs corresponds to sum of outputs).

When using linear methods in the frequency domain, the input wave system is decomposed into sinusoidal components and a response is found for each of them in terms of amplitude and phase.

The input to the procedure is represented by a spectral representation of the sea encountered by the ship. Responses, for a ship in a given condition, depend on the input sea characteristics (spectrum and spatial distribution respect to the ship course).

The output consists of response spectra of point pressures on the hull and of the other derived responses, such as global loads and ship motions. Output spectra can be used to derive short and long-term predictions for the probability distributions of the responses and of their extreme values (see Subsection 18.3.4.5).

Despite the numerous and demanding simplifications at the basis of the procedure, strip theory methods, developed since the early 60s, have been validated over time in several contexts and are extensively used for predictions of wave loads.

In principle, the base assumptions of the method are valid only for small wave excitations, small motion responses and low speed of the ship.

In practice, the field of successful applications extends far beyond the limits suggested by the preservation of realism in the base assumptions: the method is actually used extensively to study even extreme loads and for fast vessels.

18.3.4.4 Limits of linear methods for wave loads

Due to the simplifications adopted on boundary conditions to linearize the problem of ship response in waves, results in terms of hydrodynamic pressures are given always up to the still water level, while in reality the pressure distribution extends over the actual wetted surface. This represents a major problem when dealing with local loads in the side region close to the waterline.

Another effect of basic assumptions is that all responses at a given frequency are represented by sinusoidal fluctuations (symmetric with respect to a zero mean value). A consequence is that all the derived global wave loads also have the same characteristics, while, for example, actual values of vertical bending moment show marked differences between the hogging and sagging conditions. Corrections to account for this effect are often used, based on statistical data (7) or on more advanced non-linear methods.

A third implication of linearization regards the superimposition of static and dynamic loads. Dynamic loads are evaluated separately from the static ones and later summed up: this results in an un-physical situation, in which weight forces (included only in static loads) are considered as acting always along the vertical axis of the ship reference system (as in still water). Actually, in a seaway, weight forces are directed along the *true vertical* direction, which depends on roll and pitch angles, having therefore also cOI1Jlonents in the longitudinal and lateral direction of the ship.

This aspect represents one of the intrinsic non-linearities in the actual system, as the direction of an external input force (weight) depends on the response of the system itself (roll and pitch angles).

This effect is often neglected in the practice, where linear superposition of still water and wave loads is largely followed.

18.3.4.5 Wave loads probabilistic characterization

The most widely adopted method to characterize the loads in the probability domain is the so-called spectral method, used in conjunction with linear frequency-domain methods for the solution of the ship-wave interaction problem.

From the frequency domain analysis response spectra S/ 0)) are derived, which can be integrated to obtain spectral moments m_n of order n (equation 13).

$$m_{ny} = \int_0^\infty \omega^n S_y(\omega) d\omega \qquad [13]$$

This information is the basis of the spectral method, whose theoretical framework (main hypotheses, assumptions and steps) is recalled in the following.

If the stochastic process representing the wave input to the ship system is modeled as a *stationary* and *ergodic Gaussian* process *with zero mean*, the response of the system (load) can be modeled as a process having the same characteristics.

The *Parseval* theorem and the ergodicity property establish a correspondence between the area of the response spectrum (spectral moment of order 0: ffioy) and the variance of its Gaussian probability distribution (14). This allows expressing the density probability distribution of the Gaussian response y in terms of ffioy (equation 14).

$$f_Y(y) = \frac{1}{\sqrt{2\pi m_{0Y}}} e^{-\left(y^2/2m_{0Y}^2\right)} \qquad [14]$$

Equation 14 expresses the distribution ofthe fluctuating response *y* at a generic time instant.

From a structural point of view, more interesting data are represented by:

- the probability distribution of the response at selected time instants, corresponding to the highest values in each zero-crossing period *(peaks:* variable p),
- the probability distribution of the excursions between the highest and the lowest value in each zero-crossing period *(range:* variable r), and
- the probability distribution of the highest value in the whole stationary period of the phenomenon *(extreme value* in period Ts' variable extrTsy).

The aforementioned distributions can be derived from the underlying Gaussian distribution of the response (equation 14) in the additional hypotheses of *narrow band* response process and of *independence between peaks.* The first two probability distributions take the form of equations 15 and 16 respectively, both Rayleigh density distributions (see 14).

The distribution in equation 16 is particularly interesting for fatigue checks, as it can be adopted to describe stress ranges of fatigue cycles.

$$f_P(p) = \frac{p}{m_0} \exp\left(-\frac{p^2}{2m_0}\right) \qquad [15]$$

$$f_R(r) = \frac{r}{4m_0} \exp\left(-\frac{r^2}{8m_0}\right) \qquad [16]$$

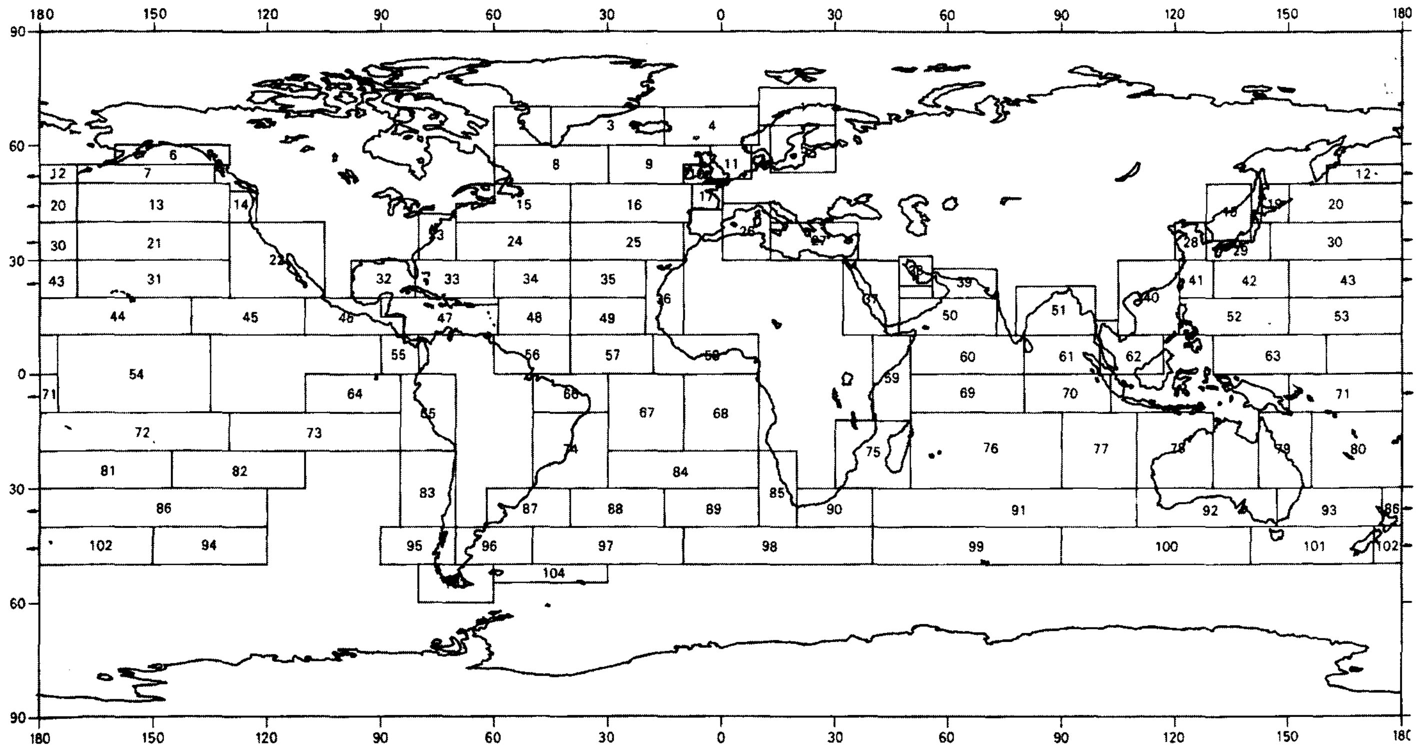

Figure 18.11 Map of Sea Zones of the World (15)

- *sea description:* as above mentioned, scatter diagrams are derived from direct observations on the field, which are affected by a certain degree of indetermination.

  In addition, simplified sea spectral shapes are adopted, based on a limited number of parameters (generally, bi-parametric formulations based on significant wave and mean wave period),
- *modelfor the ship's response:* as briefly outlined in Sub-section 18.3.4.3, the model is greatly simplified, p'ljticularly as regards fluid characteristics and boundary conditions.

  Numerical algorithms and specific procedures adopted for the solution also influence results, creating differences even between theoretically equivalent methods, and
- *the de-conditioning procedure* adopted to derive long term predictions from short term ones can add further uncertainties.

18.3.5 Local Loads

As previously stated, local loads are applied to individual structural members like panels and beams (stiffeners or primary supporting members).

They are once again traditionally divided into static and dynamic loads, referred respectively to the situation in still water and in a seaway.

Contrary to strength verifications of the hull girder, which are nowadays largely based on ultimate limit states (for example, in longitudinal strength: ultimate bending moment), checks on local structures are still in part implicitly based on more conservative limit states (yield strength).

In many Rules, reference (characteristic) local loads, as well as the motions and accelerations on which they are based, are therefore implicitly calibrated at an exceeding probability higher than the 10^{-8} value adopted in global load strength verifications.

18.3.6 External Pressure Loads

Static and dynamic pressures generated on the wet surface of the hull belong to external loads. They act as local transverse loads for the hull plating and supporting structures.

18.3.6.1 Static external pressures

Hydrostatic pressure is related through equation 20 to the vertical distance between the free surface and the load point (static head h_S)'

$$Ps = \rho g h_S \qquad [20]$$

In the case of the external pressure on the hull, hs corresponds to the local draft of the load point (reference is made to design waterline).

18.3.6.2 Dynamic pressures

The pressure distribution, as well as the wet portion of the hull, is modified for a ship in a seaway with respect to the still water (Figure 18.9). Pressures and areas of application are in principle obtained solving the general problem of ship motions in a seaway.

Approximate distributions of the wave external pressure, to be added to the hydrostatic one, are adopted in Classification Rules for the ship in various load cases (Figure 18.12).

18.3.7 Internal Loads-Liquid in Tanks

Liquid cargoes generate normal pressures on the walls of the containing tank. Such pressures represent a local transversalload for plate, stiffeners and primary supporting members of the tank walls.

18.3.7.1 Static internal pressure

For a ship in still water, gravitation acceleration g generates a hydrostatic pressure, varying again according to equation 20. The static head hs corresponds here to the vertical distance from the load point to the highest part of the tank, increased to account for the vertical extension over that point of air pipes (that can be occasionally filled with liquid) or, if applicable, for the ullage space pressure (the pressure present at the free surface, corresponding for example to the setting pressure of outlet valves).

18.3.7.2 Dynamic internal pressure

When the ship advances in waves, different types of motions are generated in the liquid contained in a tank onboard, depending on the period of the ship motions and on the filling level: the internal pressure distribution varies accordingly.,

In a *completely full tank,* fluid internal velocities relative to the tank walls are small and the acceleration in the fluid is considered as corresponding to the global ship acceleration ~.

The total pressure (equation 21) can be evaluated in terms of the total acceleration ar, obtained summing ~ to gravity g.

The gravitational acceleration g is directed according to the *true vertical.* This means that its components in the ship reference system depend on roll and pitch angles (in Figure 18.13 on roll angle er>-

$$Pf = parhT \qquad [21]$$

In equation 21, h_T is the distance between the load point and the highest point of the tank in the direction of the total acceleration vector ar (Figure 18.13)

If the tank is only *partially filled,* significant fluid internal velocities can arise in the longitudinal and/or transversal directions, producing additional pressure loads (sloshing loads).

If pitch or roll frequencies are close to the tank resonance frequency in the inherent direction (which can be evaluated on the basis of geometrical parameters and filling ratio), kinetic energy tends to concentrate in the fluid and sloshing phenomena are enhanced.

The resulting pressure field can be quite complicated and specific simulations are needed for a detailed quantification. Experimental techniques as well as 2D and 3D procedures have been developed for the purpose. For more details see references 16 and 17.

A further type of excitation is represented by impacts that can occur on horizontal or sub-horizontal plates of the upper part of the tank walls for high filling ratios and, at low filling levels, in vertical or sub-vertical plates of the lower part of the tank.

Impact loads are very difficult to characterize, being related to a number of effects, such as: local shape and velocity of the free surface, air trapping in the fluid and response of the structure. A complete model of the phenomenon would require a very detailed two-phase scheme for the fluid and a dynamic model for the structure including hydro-elasticity effects.

Simplified distributions of sloshing and/or impact pressures are often provided by Classification Societies for structural verification (Figure 18.14).

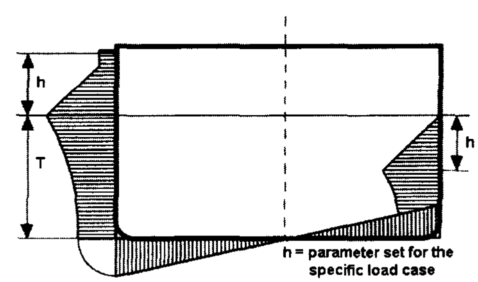

Figure 18.12 Example of Simplified Distribution of External Pressure (10)

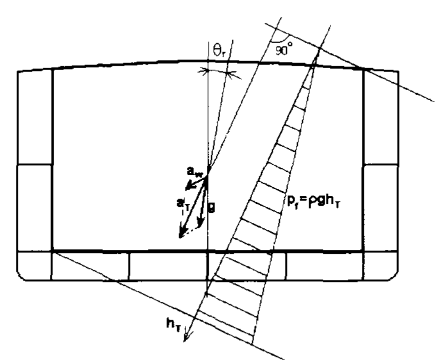

Figure 18.13 Internal Fluid Pressure (full tank)

18.3.7.3 Dry bulk cargo

In the case of a dry bulk cargo, internal friction forces arise within the cargo itself and between the cargo and the walls of the hold. As a result, the component normal to the wall has a different distribution from the load corresponding to a liquid cargo of the same density; also additional tangential components are present.

18.3.8 Inertial Loads-Dry Cargo

To account for this effect, distributions for the components of cargo load are approximated with empirical formulations based on the material frictional characteristics, usually expressed by the angle of repose for the bulk cargo, and on the slope of the wall. Such formulations cover both the static and the dynamic cases.

18.3.8.1 Unit cargo

In the case of a unit cargo (container, pallet, vehicle or other) the local translational accelerations at the centre of gravity are applied to the mass to obtain a distribution of inertial forces. Such forces are transferred to the structure in different ways, depending on the number and extension of contact areas and on typology and geometry of the lashing or supporting systems.

Generally, this kind of load is modelled by one or more concentrated forces (Figure 18.15) or by a uniform load applied on the contact area with the structure.

The latter case applies, for example, to the inertial loads transmitted by tyred vehicles when modelling the response of the deck plate between stiffeners: in this case the load is distributed uniformly on the tyre print.

18.3.9 DynamicLoads!

18.3.9.1 Slamming and bow flare loads

When sailing in heavy seas, the ship can experience such large heave motions that the forebody emerges completely from the water. In the following downward fall, the bottom of the ship can hit the water surface, thus generating considerable impact pressures.

The phenomenon occurs in flat areas of the forward part of the ship and it is strongly correlated to loading conditions with a low forward draft.

It affects both local structures *(bottom panels)* and the global bending behaviour of the hull girder with generation also of free vibrations at the first vertical flexural modes for the hull *(whipping)*.

A full description of the slamming phenomenon involves a number of parameters: amplitude and velocity of ship motions relative to water, Ipcal angle formed at impact between the flat part of the hull and the water free surface, presence and extension of air trapped between fluid and ship bottom and structural dynamic behavior (18,19).

While slamming probability of occurrence can be studied on the basis only of predictions of ship relative motions (which should in principle include non-linear effects due to extreme motions), a quantification of slamming pressure involves necessarily all the other mentioned phenomena and is very difficult to attain, both from a theoretical and experimental point of view (18,19).

From a practical point of view, Class Societies prescribe, for ships with loading conditions corresponding to a low fore

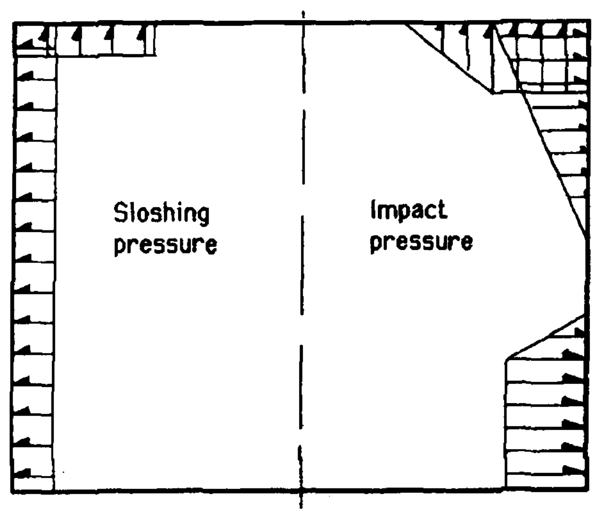

Figure 18.14 Example of Simplified Distributions of Sloshing and Impact Pressures (11)

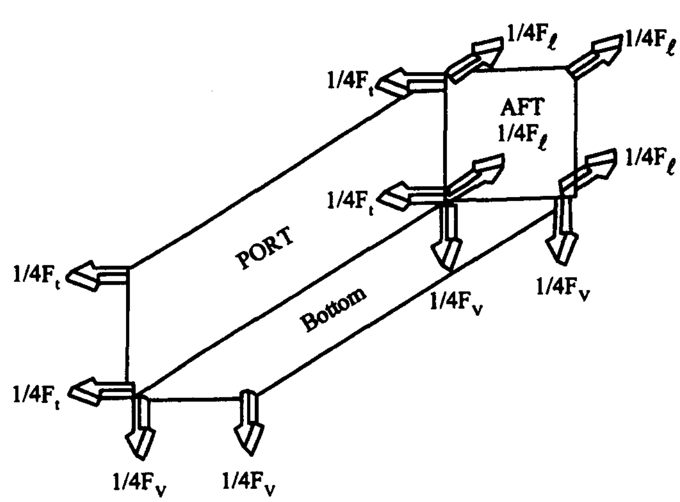

Figure 18.15 Scheme of Local Forces Transmitted by a Container to the Support System (8)

draft, local structural checks based on an additional external pressure.

Such additional pressure is formulated as a function of ship main characteristics, of local geometry of the ship (width of flat bottom, local draft) and, in some cases, ofthe first natural frequency of flexural vibration of the hull girder.

The influence on global loads is accounted for by an additional term for the vertical wave-induced bending moment, which can produce a significant increase (15% and more) in the design value.

A phenomenon quite similar to bottom slamming can occur also on the forebody of ships with a large bow flare. In this case dynamic and (to a lesser extent) impulsive pressures are generated on the sides of V-shaped fore sections.

The phenomenon is likely to occur quite frequently on ships prone to it, but with lower pressures than in bottom slamming. The incremental effect on vertical bending moment can however be significant.

A quantification of bow flare effects implies taking into account the variation of the local breadth of the section as a function of draft. It represents a typical non-linear effect (non-linearity due to hull geometry).

Slamming can also occur in the rear part of the ship, when the flat part of the stem counter is close to surface.

18.3.9.2 Springing

Another phenomenon which involves the dynamic response of the hull girder is springing. For particular types of ships, a coincidence can occur between the frequency of wave excitation and the natural frequency associated to the first (two-node) flexural mode in the vertical plane, thus producing a resonance for that mode (see also Subsection 18.6.8.2).

The phenomenon has been observed in particular on Great Lakes vessels, a category of ships long and flexible, witt comparatively low resonance frequencies (1, Chapter VI).

The exciting action has an origin similar to the case of quasi-static wave bending moment and can be studied with the same techniques, but the response in terms of deflection and stresses is magnified by dynamic effects. For recent developments of research in the field (see references 16 and 17).

18.3.9.3 Propeller induced pressures and forces

Due to the wake generated by the presence of the after part of the hull, the propeller operates in a non-uniform incident velocity field.

Blade profiles experience a varying angle of attack during the revolution and the pressure field generated around the blades fluctuates accordingly.

The dynamic pressure field impinges the hull plating in the stem region, thus generating an exciting force for the structure.

A second effect is due to axial and non axial forc~s and moments generated by the propeller on the shaft and transmitted through the bearings to the hull (bearing forces).

Due to the negative dynamic pressure generated by the increased angle of attack, the local pressure on the back of blade profiles can, for any rotation angle, fall below the vapor saturation pressure. In this case, a vapor sheet is generated on the back of the profile (cavitation phenomenon). The vapor filled cavity collapses as soon as the-angle of attack decreases in the propeller revolution and the local pressure rises again over the vapor saturation pressure.

Cavitation further enhances pressure fluctuations, because of the rapid displacement of the surrounding water volume during the growing phase of the vapor bubble and because of the following implosion when conditions for its existence are removed.

All of the three mentioned types of excitation have their main components at the propeller rotational frequency, at the blade frequency, and at their first harmonics. In addition to the above frequencies, the cavitation pressure field contains also other components at higher frequency, related to the dynamics of the vapor cavity.

Propellers with skewed blades perform better as regards induced pressure, because not all the blade sections pass simultaneously in the region of the stem counter, where disturbances in the wake are larger; accordingly, pressure fluctuations are distributed over a longer time period and peak values are lower.

Bearing forces and pressures induced on the stem counter by cavitating and non cavitating propellers can be calculated with dedicated numerical simulations (18).

18.3.9.4 Main engine excitation

Another major source of dynamic excitation for the hull girder is represented by the main engine. Depending on general arrangement and on number of cylinders, diesel engines generate internally unbalanced forces and moments, mainly at the engine revolution frequency, at the cylinders firing frequency and inherent harmonics (Figure 18.16).

The excitation due to the first harmonics of low speed diesel engines can be at frequencies close to the first natural hull girder frequencies, thus representing a possible cause of a global resonance.

In addition to frequency coincidence, also direction and location of the excitation are important factors: for example, a vertical excitation in a nodal point of a vertical flexural mode has much less effect in exciting that mode tha.n the same excitation placed on a point of maximum modal deflection.

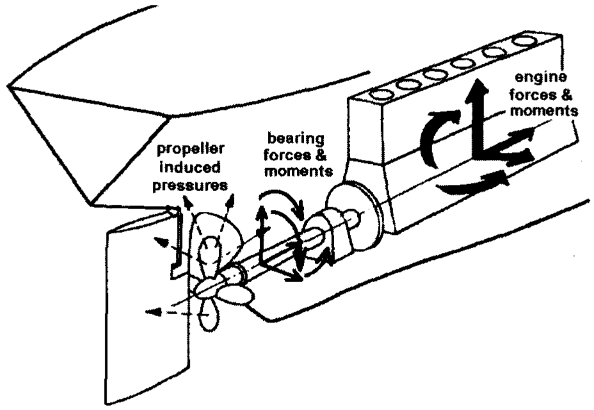

Figure 18.16 Propeller, Shaft and Engine Induced Actions (20)

In addition to low frequency hull vibrations, components at higher frequencies from the same sources can give rise to resonance in local structures, which can be predicted by suitable dynamic structural models (18,19).

18.3.10 Other Loads

18.3.10.1 Thermal loads

A ship experiences loads as a result of thermal effects, which can be produced by external agents (the sun heating the deck), or internal ones (heat transfer from/to heated or refrigerated cargo).

What actually creates stresses is a non-uniform temperature distribution, which implies that the warmer part of the structure tends to expand while the rest opposes to this deformation. A peculiar aspect of this situation is that the portion of the structure in larger elongation is compressed and vice-versa, which is contrary to the normal experience.

It is very difficult to quantify thermal loads, th' main problems being related to the identification of the temperature distribution and in particular to the model for constraints. Usually these loads are considered only in a qualitative way (1, Chapter VI).

18.3.10.2 Mooring loads

For a moored vessel, loads are exerted from external actions on the mooring system and from there to the local supporting structure. The main contributions come by wind, waves and current.

Wind: The force due to wind action is mainly directed in the direction of the wind (drag force), even if a limited component in the orthogonal direction can arise in particular situations. The magnitude depends on the wind speed and on extension and geometry of the exposed part of the ship. The action due to wind can be described in terms of two force components; a longitudinal one F_{WiL}, and a transverse one F_{WiT} (equation 22), and a moment M_{Wiz} about the vertical axis (equation 23), all applied at the center of gravity.

$$F_{WiL,T} = 1/2\, C_{FL,T}(\phi_{Wi})\, \phi\, A_{Wi}\, V_{Wi}^2 \qquad [22]$$

$$M_{Wiz} = 1/2\, C_{Mz}(\phi_{Wi})\, \phi\, A_{Wi}\, L\, V_{Wi}^2 \qquad [23]$$

where:

ϕ_{Wi} = the angle formed by the direction of the wind relative to the ship

$C_{Mz}(\phi_{Wi})$, $C_{FL}(\phi_{Wi})$, $C_{FT}(\phi_{Wi})$ are all coefficients depending on the shape of exposed part of the ship and on angle ϕ_{Wi}

A_{Wi} = the reference area for the surface of the ship exposed to wind, (usually the area of the cross section)

V_{Wi} = the wind speed

The empirical formulas in equations 22 and 23 account also for the tangential force acting on the ship surfaces parallel to the wind direction.

Current: The current exerts on the immersed part of the hull a similar action to the one of wind on the emerged part (drag force). It can be described through coefficients and variables analogous to those of equations 22 and 23.

Waves: Linear wave excitation has in principle a sinusoidal time dependence (whose mean value is by definition zero). If ship motions in the wave direction are not constrained (for example, if the anchor chain is not in tension) the ship motion follows the excitation with similar time dependence and a small time lag. In this case the action on the mooring system is very small (a few percent of the other actions).

If the ship is constrained, significant loads arise on the mooring system, whose amplitude can be of the same order of magnitude of the stationary forces due to the other actions.

In addition to the linear effects discussed above, non-linear wave actions, with an average value different from zero, are also present, due to potential forces of higher order, formation of vortices, and viscous effects. These components can be significant on off-shore floating structures, which often feature also complicated mooring systems: in those cases the dynamic behavior of the mooring system is to be included in the analysis, to solve a specific motion problem. For common ships, non-linear wave effects are usually neglected.

A practical rule-of-thumb for taking into account wave actions for a ship at anchor in non protected waters is to increase of75 to 100% the sum of the other force components.

Once the total force on the ship is quantified, the tension in the mooring system (hawser, rope or chain) can be derived by force decomposition, taking into account the angle formed with the external force in the horizontal and/or vertical plane.

18.3.10.3 Launching loads

The launch is a unique moment in the life of the ship. For a successful completion of this complex operation, a number of practical, organizational and technical elements are to be kept under control (as general reference see reference 1, Chapter XVII).

Here only the aspect of loads acting on the ship will be discussed, so, among the various types oflaunch, only those which present peculiarities as regards ship loads will be considered: end launch and side launch.

End Launch: In end launch, resultant forces and motions are contained in the longitudinal plane of the ship (Figure 18.17).

The vessel is subjected to vertical sectional forces distributed along the hull girder: weight w(x), buoyancy bL(x) and the sectional force transmitted from the ground way to the cradle and from the latter to the ship's bottom (in the following: sectional cradle force fc(x), with resultant Fe).

While the weight distribution and its resultant force (weight W) are invariant during launching, the other distributions change in shape and resultant: the derivation of launching loads is based on the computation of these two distributions.

Such computation, repeated for various positions of the cradle, is based on the global static equilibrium (equations 24 and 25, in which dynamic effects are neglected: quasi static approach).

$$B_T + F_C - W = 0 \qquad [24]$$

$$x_B\, B_T + x_F\, F_C - x_W\, W = 0 \qquad [25]$$

where:

W, B_T, F_e = (respectively) weight, buoyancy and cradle force resultants

x_W, x_B, x_F = their longitudinal positions

In a first phase of launching, when the cradle is still in contact for a certain length with the ground way, the buoyancy distribution is known and the cradle force resultant and position is derived.

In a second phase, beginning when the cradle starts to rotate (pivoting phase: Figure 18.18), the position x_F corresponds steadily to the fore end of the cradle and what is unknown is the magnitude of Fe and the actual aft draft of the ship (and consequently, the buoyancy distribution).

The total sectional vertical force distribution is found as the sum of the three components (equation 26) and can be integrated according to equations 1 and 2 to derive vertical shear and bending moment.

$$q_{VL}(X) = w(x) - b_L(x) - f_c(x) \qquad \{26]$$

This computation is performed for various intermediate positions of the cradle during the launching in order to check all phases. However, the most demanding situation for the hull girder corresponds to the instant when pivoting starts.

In that moment the cradle force is concentrated close to the bow, at the fore end of the cradle itself (on the *fore poppet,* if one is fitted) and it is at the maximum value.

A considerable sagging moment is present in this situation, whose maximum value is usually lower than the design one, but tends to be located in the fore part of the ship, where bending strength is not as high as at midship.

Furthermore, the ship at launching could still have temporary openings or incomplete structures (lower strength) in the area of maximum bending moment.

Another matter of concern is the concentrated force at the fore end of the cradle, which can reach a significant percentage of the total weight (typically 20-30%). It represents a strong local load and often requires additional temporary internal strengthening structures, to distribute the force on a portion of the structure large enough to sustain it.

Side Launch: In side launch, the main motion components are directed in the transversal plane of the ship (see Figure 18.19, reproduced from reference 1, Chapter XVII).

The vertical reaction from ground ways is substituted in a comparatively short time by buoyancy forces when the ship tilts and drops into water.

The kinetic energy gained during the tilting and dropping phases makes the ship oscillate around her final posi-

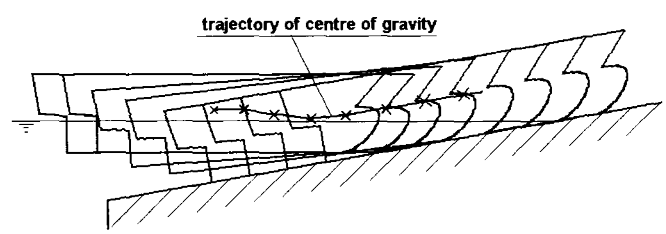

Figure 18.17 End Launch: Sketch

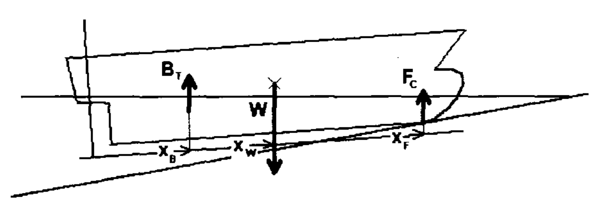

Figure 18.18 Forces during Pivoting

tion at rest. The amplitude of heave and roll motions and accelerations governs the magnitude of hull girder loads. Contrary to end launch, trajectory and loads cannot be studied as a sequence of quasi-static equilibrium positions, but need to be investigated with a dynamic analysis.

The problem is similar to the one regarding ship motions in waves, (Subsection 18.3.4), with the difference that here motions are due to a free oscillation of the system due to an unbalanced initial condition and not to an external excitation.

Another difference with respect to end launch is that both ground reaction (first) and buoyancy forces (later) are always distributed along the whole length of the ship and are not concentrated in a portion of it.

18.3.10.4 Accidentalloads

Accidental loads (collision and grounding) are discussed in more detail by [SSC (21).

Collision: When defining structural loads due to collisions, the general approach is to model the dynamics of the accident itself, in order to define trajectories of the unit(s) involved.

In general terms, the dynamics of collision should be formulated in six degrees of freedom, accounting for a number of forces acting during the event: forces induced by propeller, rudder, waves, current, collision forces between the units, hydrodynamic pressure due to motions.

Normally, theoretical models confine the analysis to components in the horizontal plane (3 degrees of freedom) and to collision forces and motion-induced hydrodynamic pressures. The latter are evaluated with potential methods of the same type as those adopted for the study of the response of the ship to waves.

As regards collision forces, they can be described differently depending on the characteristics of the strucl(tbject (ship, platform, bridge pylon ...) with different combinations of rigid, elastic or an elastic body models.

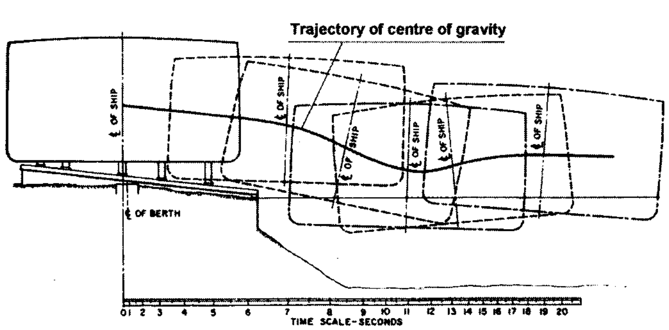

Figure 18.19 Side Launch (1, Chapter XVII)

Governing equations for the problem are given by conservation of momentum and of energy. Within this fram~-work, time domain simulations can evaluate the magnitude of contact forces and the energy, which is absorbed by structure deformation: these quantities, together with the response characteristics of the structure (energy absorption capacity), allow an evaluation of the damage penetration (21).

Grounding: In grounding, dominant effects are forces and motions in the vertical plane.

As regards forces, main components are contact forces, developed at the first impact with the ground, then friction, when the bow slides on the ground, and weight.

From the point of view of energy, the initial kinetic energy is (a) dissipated in the deformation of the lower part of the bow (b) dissipated in friction of the same area against the ground, (c) spent in deformation work of the ground (if soft: sand, gravel) and (d) converted into gravitational potential energy (work done against the weight force, which resists to the vertical raising of the ship barycenter).

In addition to soil characteristics, key parameters for the description are: slope and geometry of the ground, initial speed and direction of the ship relative to ground, shape of the bow (with/without bulb).

The final position (grounded ship) governs the magnitude of the vertical reaction force and the distribution of shear and sagging moment that are generated in the hull girder. Figure 18.20 gives an idea of the magnitude of grounding loads for different combinations of ground slopes and coefficients of friction for a 150000 tanker (results of simulations from reference 22).

In addition to numerical simulations, full and model scale tests are performed to study grounding events (21).

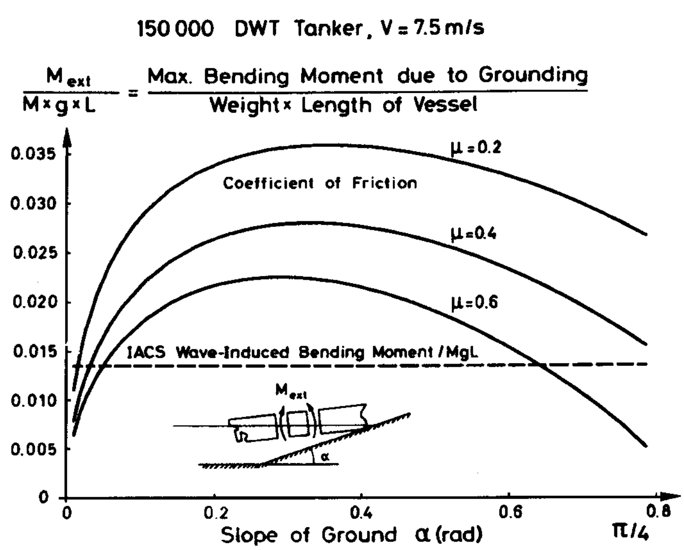

Figure 18.20 Sagging Moments for a Grounded Ship: Simulation Results (22)

18.3.11 Combination of Loads

When dealing with the characterization of a set of loads acting simultaneously, the interest lies in the definition of a total loading condition with the required exceeding probability (usually the same of the single components). This cannot be obtained by simple superposition of the characteristic values of single contributing loads, as the probability that all design loads occur at the same time is much lower than the one associated to the single component.

In the time domain, the combination problem is expressed in terms of time shift between the instants in which characteristic values occur.

In the probability domain, the complete formulation of the problem would imply, in principle, the definition of a joint probability distribution of the various loads, in order to quantify the distribution for the total load. An approximation would consist in modeling the joint distribution through its first and second order moments, that is mean values and covariance matrix (composed by the variances of the single variables and by the covariance calculated for each couple of variables). However, also this level of statistical characterization is difficult to obtain.

As a practical solution to the problem, empirically based *load cases* are defined in Rules by means of combination coefficients (with values generally::; 1) applied to single loads. Such load cases, each defined by a set of coefficients, represent realistic and, in principle, equally probable combinations of characteristic values of elementary loads.

Structural checks are performed for all load cases. The result of the verification is governed by the one, which turns out to be the most conservative for the specific structure. This procedure needs a higher number of checks (which, on the other hand, can be easily automated today), but ~lows considering various load situations (defined with different combinations of the same base loads), without choosing *a priori* the worst one.

18.3.12 New Trends and Load Non-linearities

A large part of research efforts is still devoted to a better definition of wave loads. New procedures have been proposed in the last decades to improve traditional 2D linear methods, overcoming some of the simplifications adopted to treat the problem of ship motions in waves. For a complete state of the art of computational methods in the field, reference is made to (23). A very coarse classification of the main features of the procedures reported in literature is here presented (see also reference 24).

18.3.12.1 2D versus 3D models

Three-dimensional extensions of linear methods are available; some non-linear methods have also 3-D features, while in other cases an intermediate approach is followed, with boundary conditions formulated part in 2D, part in 3D.

18.3.12.2 Body boundary conditions

In linear methods, body boundary conditions are set with reference to the mean position of the hull (in still water). Perturbation terms take into account, in the frequency or in the time domain, first order variations of hydrodynamic and hydrostatic coefficients around the still water line.

Other non-linear methods account for perturbation terms of a higher order. In this case, body boundary conditions are still linear (mean position of the hull), but second order variations of the coefficients are accounted for.

Mixed or *blending* procedures consist in linear methods modified to include non-linear effects in a single component of the velocity potential (while the other ones are treated linearly). In particular, they account for the actual geometry of wetted hull (non-linear body boundary condition) in the Froude-Krylov potential only. This effect is believed to have a major role in the definition of global loads.

More evolved (and complex) methods are able to take properly into account the exact body boundary condition (actual wetted surface of the hull).

18.3.12.3 Free surface boundary conditions

Boundary conditions on free surface can be set, depending on the various methods, with reference to: (a) a free stream at constant velocity, corresponding to ship advance, (b) a *double body* flow, accounting for the disturbance induced by the presence of a fully immersed double body hull on the uniform flow, (c) the flow corresponding to the steady advance ofthe ship in calm water, considering the free surface or (d) the incident wave profile (neglecting the interaction with the hull).

Works based on fully non-linear formulations of the free surface conditions have also been published.

18.3.12.4 Fluid characteristics

All the methods above recalled are based on an inviscid fluid potential scheme.

Some results have been published of viscous flow models based on the solution of Reynolds Averaged Navier Stokes (RANS) equations in the time domain. These methods represent the most recent trend in the field of ship motions and loads prediction and their use is limited to a few research groups.

18.4 STRESSES AND DEFLECTIONS

The reactions of structural components of the ship hull to external loads are usually measured by either stresses or deflections. Structural performance criteria and the associated analyses involving stresses are referred to under the general term of *strength.* The strength of a structural component would be inadequate if it experiences a loss of load-carrying ability through material fracture, yield, buckling, or some other failure mechanism in response to the applied loading. Excessive deflection may also limit the structural effectiveness of a member, even though material failure does not occur, if that deflection results in a misalignment or other geometric displacement of vital components of the ship's machinery, navigational equipment, etc., thus rendering the system ineffective.

The present section deals with the determination of the responses, in the form of stress and deflection, of structural members to the applied loads. Once these responses are known it is necessary to determine whether the structure is adequate to withstand the demands placed upon it, and this requires consideration of the different *failure modes* associated to the *limit states,* as discussed in Sections 18.5 and 18.6

Although longitudinal strength under vertical bending moment and vertical shear forces is the first important strength consideration in almost all ships, a number of other strength considerations must be considered. Prominent amongst these are transverse, torsional and horizontal bending strength, with torsional strength requiring particular attention on *open* ships with large hatches arranged close together. All these are briefly presented in this Section. More detailed information is available in Lewis (2) and Hughes (3), both published by SNAME, and Rawson (25). Note that the content of Section 18.4 is influenced mainly fntn Lewis (2).

18.4.1 Stress and Deflection Components

The structural response of the hull girder and the associated members can be subdivided into three components (Figure 18.21).

Primary response is the response of the entire hull, when the ship bends as a beam under the longitudinal distribution of load. The associated primary stresses *(σ_1)* are those, which are usually called the longitudinal bending stresses, but the general category of primary does not imply a direction.

Secondary response relates to the global bending of stiffened panels (for single hull ship) or to the behavior of double bottom, double sides, etc., for double hull ships:

- Stresses in the plating *of stiffened panel* under lateral pressure may have different origins (σ_2 and σ_2^*). For a stiffened panel, there is the stress (σ_2) and deflection of the global bending of the orthotropic stiffened panels, for example, the panel of bottom structure contained between two adjacent transverse bulkheads. The stiffener and the attached plating bend under the lateral load and the plate develops additional plane stresses since the plate acts as a flange with the stiffeners. In longitudinally framed ships there is also a second type of secondary stresses: σ_2^* corresponds to the bending under the hydrostatic pressure of the longitudinals between transverse frames (web frames). For transversally framed panels, σ_2^* may also exist and would correspond to the bending of the equally spaced frames between two stiff longitudinal girders.
- *A double bottom* behaves as box girder but can bend longitudinally, transversally or both. This global bending induces stress (σ_2) and deflection. In addition, there is also

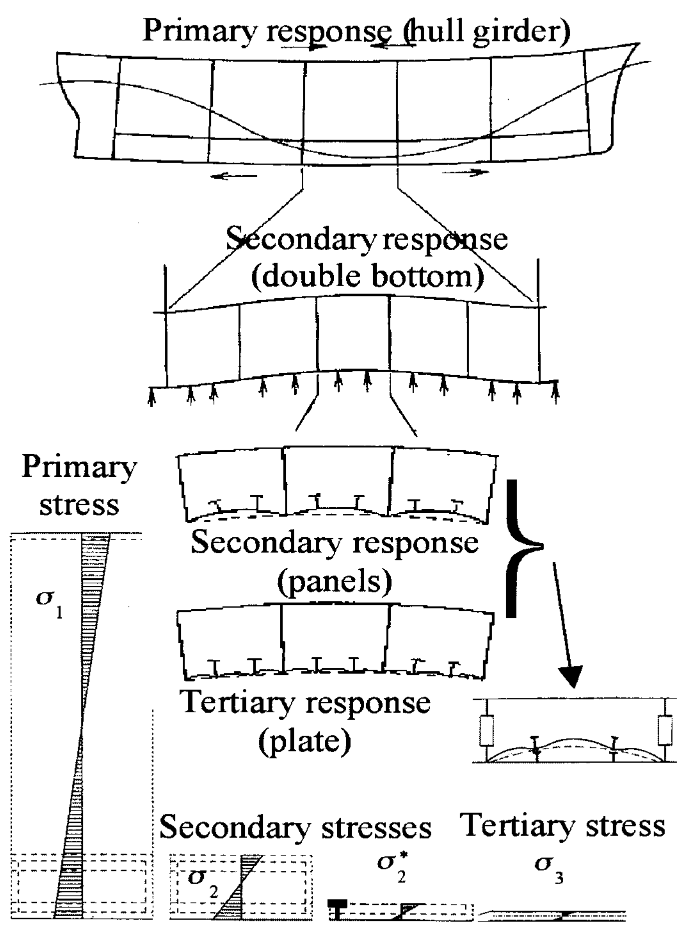

Figure 18.21 Primary (Hull), Secondary (Double Bottom and Stiffened Panels) and Tertiary (Plate) Structural Responses (1, 2)

the a_2^* stress that corresponds to the bending of the longitudinals (for example, in the inner and outer bottom) between two transverse elements (floors).

Tertiary response describes the out-of-plane deflection and associated stress of an individual unstiffened plate panel included between 2 longitudinals and 2 transverse web frames. The boundaries are formed by these components (Figure 18.22).

Primary and secondary responses induce in-plane membrane stresses, nearly uniformly distributed through the plate thickness. Tertiary stresses, which result from the bending of the plate member itself vary through the thickness, but may contain a membrane component if the out-of-plane deflections are large compared to the plate thickness.

In many instances, there is little or no interaction between the three (primary, secondary, tertiary) component stresses or deflections, and each component may be computed by methods and considerations entirely independent of the other two. The resultant stress, in such a case, is then obtained by a simple superposition of the three component stresses (Subsection 18.4.7). An exception is the case of plate (tertiary) deflections, which are large compared to the thickness of plate.

In plating, each response induces longitudinal stresses, transverse stresses and shear stresses. This is due to the *Poisson's Ratio.* Both primary and secondary stresses are bending stresses but in plating these stresses look like membrane stresses.

In stiffeners, only primary and secondary responses induce stresses in the direction of the members and shear stresses. Tertiary response has no effect on the stiffeners.

In Figure 18.21 (see also Figure 18.37) the three types of response are shown with their associated stresses (al, a_2, a_2^* and a_3). These considerations point to the inherenfsimplicity of the underlying theory. The structural naval architect deals principally with beam theory, plate theory, and combinations of both.

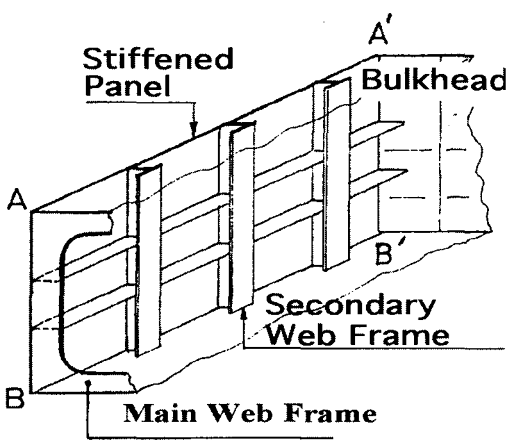

Figure 18.22 A Standard Stiffened Panel

18.4.2 Basic Structural Components

Structural components are extensively discussed in Chapter 17 - Structure Arrangement Component Design. In this section, only the basic structural component used extensively is presented. It is basically a *stiffened panel.*

The global ship structure is usually referred to as being a *box girder* or *hull girder.* Modeling of this hull girder is the first task of the designer. It is usually done by modeling the hull girder with a series of stiffened panels.

Stiffened panels are the main components of a ship. Almost any part of the ship can be modeled as stiffened panels (plane or cylindrical).

This means that, once the ship's main dimensions and general arrangement are fixed, the remaining scantling development mainly deals with stiffened panels.

The panels are joined one to another by connecting lines (edges of the prismatic structures) and have *longitudinal* and *transverse stiffening* (Figures 18.22,23 and 36).

- Longitudinal Stiffening includes
  - longitudinals (equally distributed), used only for the design of longitudinally stiffened panels,
  - girders (not equally distributed).
- TransVerse Stiffening includes (Figure 18.23)
  - transverse bulkheads (a),
  - the main transverse framing also called web-frames (equally distributed; large spacing), used for longitudinally stiffened panels (b) and transversally stiffened panels (c).

18.4.3 Primary Response

18.4.3.1 Beam model and hull section modulus

The structural members involved in the computation of primary stress are, for the most part, the longitudinally continuous members such as deck, side, bottom shell, longitudinal bulkheads, and continuous or fully effective longitudinal primary or secondary stiffening members.

Elementary beam theory (equation 29) is usually utilized in computing the component of primary stress, a_1, and deflection due to vertical or lateral hull bending loads. In assessing the applicability ofthis beam theory to ship structures, it is useful to restate the underlying assumptions:

- the beam is prismatic, that is, all cross sections are the same and there is no openings or discontinuities,
- plane cross sections remain plane after deformation, will

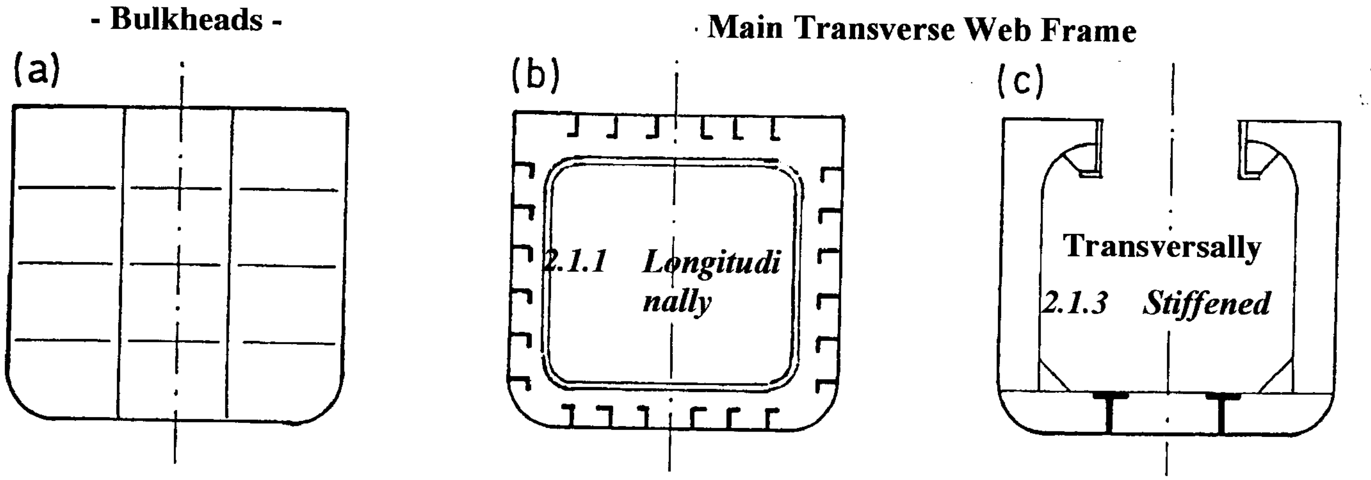

Figure 18.23 Types of Stiffening (Longitudinal and Transverse)

not deform in their own planes, and merely rotate as the beam deflects.

- transverse (Poisson) effects on strain are neglected.
- the material behaves elastically: the elasticity modulus in tension and compression is equal.
- shear effects and bending (stresses, strains) are :r;totcoupled. For torsional deformation, the effect of secondary shear and axial stresses due to warping deformations are neglected.

Since stress concentrations (deck openings, side ports, etc.) cannot be avoided in a highly complex structure such as a ship, their effects must be included in any comprehensive stress analysis. Methods dealing with stress concentrations are presented in Subsection 18.6.6.3 as they are linked to fatigue.

The elastic linear bending equations, equations 27 and 28, are derived from basic mechanic principle present<4l at Figure 18.24.

$$EI\,(\partial^2 w / \partial x^2) = M(x) \qquad [27]$$

or

$$EI\,(\partial^4 w / \partial x^4) = q(x) \qquad [28]$$

where:

w = deflection (Figure 18.24), in m
E = modulus of elasticity of the material, in N/m^2
I = moment of inertia of beam cross section about a horizontal axis through its centroid, in m^4
M(x) = bending moment, in N.m
q(x) = load per unit length in N/m
$= \partial V(x)/\partial x$
$= \partial^2 M(x)/\partial x^2$
$= EI\,(\partial^4 w/\partial x^4)$

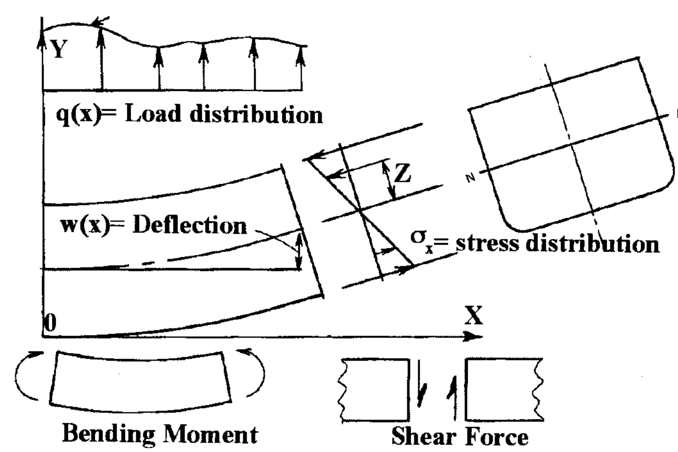

Figure 18.24 Behavior of an Elastic Beam under Shear Force and Bending Moment (2)

Hull Section Modulus: The plane section assumption together with elastic material behavior results in a longitudinal stress, 0"1' in the beam that varies linearly over the depth of the cross section.

The simple beam theory for longitudinal strength calculations of a ship is based on the hypothesis (usually attributed to Navier) that plane sections remain plane and in the absence of shear, normal to the OXY plane (Figure 18.24). This gives the well-known formula:

$$\sigma = M / (I / C) = M / SM \qquad [29]$$

where:

M = bending moment (in N.m)
σ = bending stress (in N/m^2)
I = Sectional moment of Inertia about the neutral axis (m^4)

c = distance from the neutral axis to the extreme member (m)
SM = section modulus *(I/c)* (m^3)

For a given bending moment at a given cross section of a ship, at any part of the cross section, the stress may be obtained (σ = M/SM = Mc/I) which is proportional to the distance c of that part from the neutral axis. The neutral axis will seldom be located exactly at half-depth of the section; hence two values of c and σ will be obtained for each section for any given bending moment, one for the top fiber (deck) and one for the bottom fiber (bottom shell).

A variation on the above beam equations may be of importance in ship structures. It concerns beams composed of two or more materials of different moduli of elasticity, for example, steel and aluminum. In this case, the flexural rigidity, EI, is replaced by $\int_A E(z)\, z^2\, dA$, where A is cross sectional area and E(z) the modulus of elasticity of an element of area dA located at distance z from the neutral axis. The neutral axis is located at such height that $\int_A E(z)\, z\, dA = 0$.

Calculation of Section Modulus: An important step in routine ship design is the calculation of the midship section modulus. As defined in connection with equation 29, it indicates the bending strength properties of the pnmary hull structure. The section modulus to the deck or bottom is obtained by dividing the moment of inertia by the distance from the neutral axis to the molded deck line at side or to the base line, respectively.

In general, the following items may be included in the calculation of the section modulus, provided they are continuous or effectively developed:

- deck plating (strength deck and .other effective decks). (See Subsection 18.4.3.9 for Hull/Superstructure Interaction). f
- shell and inner bottom plating,
- deck and bottom girders,
- plating and longitudinal stiffeners of longitudinal bulkheads,
- alliongitudinals of deck, sides, bottom and inner bottom, and
- continuous longitudinal hatch coamings.

In general, only members that are effective in both tension and compression are assumed to act as part of the hull girder.

Theoretically, a thorough analysis oflongitudinal strength would include the construction of a curve of section moduli throughout the length ofthe ship as shown in Figure 18.25.

Dividing the ordinates of the maximum bending-moments curve (the envelope curve of maxima) by the corresponding ordinates of the section-moduli curve yields stress values. By using both the hogging and sagging moment curves four curves of stress can be obtained; that is, tension and compression values for both top and bottom extreme fiber~.

It is customary, however, to assume the maximum bending moment to extend over the midship portion of the ship. Minimum section modulus most often occurs at the location of a hatch or a deck opening. Accordingly, the classification societies ordinarily require the maintenance of the midship scantlings throughout the midship four-tenths length. This practice maintains the midship section area of structure practically at full value in the vicinity of maximum shear as well as providing for possible variation in the precise location of the maximum bending moment.

Lateral Bending Combined with Vertical Bending: Up to this point, attention has been focused principally upon the vertical longitudinal bending response of the hull. As the ship moves through a seaway encountering waves from directions other than directly ahead or astern, it will experience lateral bending loads and twisting moments in addition to the vertical loads. The former may be dealt with by methods that are similar to those used for treating the vertical bending loads, noting that there will be no component of still water bending moment or shear in the lateral direction. The twisting or torsional loads will require some special consideration. Note that the response of the ship to the overall hull twisting loading should be considered also a primary response.

The combination of vertical and horizontal bending moment has as major effect to increase the stress at the extreme comers of the structure (equation 30).

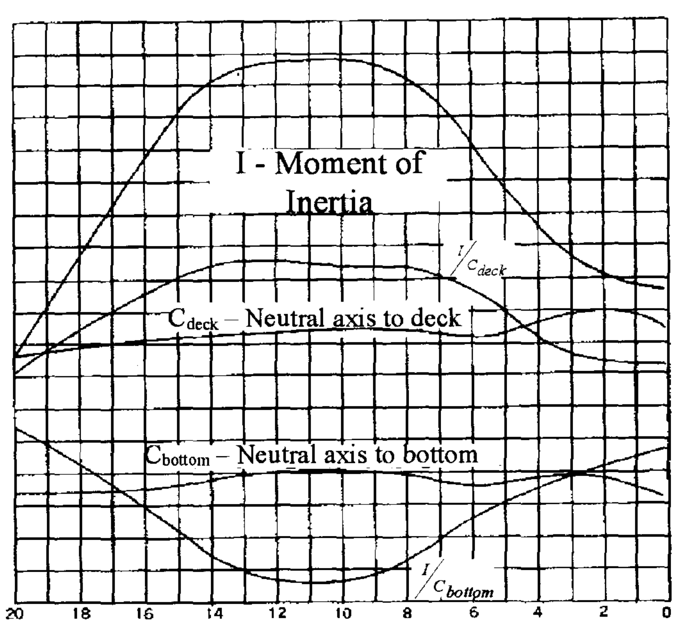

Figure 18.25 Moment of Inertia and Section Modulus (1)

$$\sigma = \frac{M_v}{(I_v / c_v)} + \frac{M_h}{(I_h / c_h)} \qquad [30]$$

where M_v, I_v, c_v, and M_h, I_h, c_h, correspond to the M, I, c defined in equation 29, for the vertical bending and the horizontal bending respectively.

For a given vertical bending (M_v), the periodical wave induced horizontal bending moment (M_h) increases stresses, alternatively, on the upper starboard and lower portside, and on the upper portside and lower starboard. This explains why these areas are usually reinforced.

Empirical interaction formulas between vertical bending, horizontal bending and shear related to ultimate strength of hull girder are given in Subsection 18.6.5.2.

Transverse Stresses: With regards to the validity of the Navier Equation (equation 29), a significant improvement may be obtained by considering a longitudinal strength member composed of thin plate with transverse framing. This might, for example, represent a portion of the deck structure of a ship that is subject to a longitudinal stress σ_x, from the primary bending of the hull girder. As a result of the longitudinal strain, ε_x, which is associated with σ_x, there will exist a transverse strain, ε_s. For the case of a plate that is free of constraint in the transverse direction, the two strains will be of opposite sign and the ratio of their absolute values, given by $| \varepsilon_s / \varepsilon_x | = \nu$, is a constant property of the material. The quantity ν is called *Poisson's Ratio* and, for steel and aluminum, has a value of approximately 0.3.

Hooke's Law, which expresses the relation between stress and strain in two dimensions, may be stated in terms of the plate strains (equation 31). This shows that the primary response induces both longitudinal (σ_x) and transversal stresses (σ_s) in plating.

$$\begin{aligned} \varepsilon_x &= 1 / E\, (\sigma_x - \nu\, \sigma_S) \\ \varepsilon_S &= 1 / E\, (\sigma_S - \nu\, \sigma_x) \end{aligned} \qquad [31]$$

As transverse plate boundaries are usually constrained (displacements not allowed), the transverse stress can be taken, in first approximation as:

$$\sigma_s = \nu\, \sigma_x \qquad [32]$$

Equation 32 is only valid to assess the additional stresses in a given direction induced by the stresses in the perpendicular direction computed, for instance, with the Navier equation (equation 29).

18.4.3.2 Shear stress associated to shear forces

The simple beam theory expressions given in the preceding section permit evaluation the longitudinal component of the primary stress, σ_x. In Figure 18.26, it can be seen that an element of side shell or deck plating may, in general be subject to two other components of stress, a direct stress in the transverse direction and a shearing stress.

This figure illustrates these as the *stress resultants*, defined as the stress multiplied by plate thickness.

The stress resultants (N/m) are given by the following expressions:

$N_x = t\, \sigma_x$ and $Ns = t\, \sigma_s$ stress resultants, in N/m

$N = t\, \tau$ shear stress resultant or *shear flow,* in N/m

where:

σ_x, σ_s = stresses in the longitudinal and transverse directions, in N/m²
τ = shear stress, in N/m²
t = plate thickness, in m

In many parts of the ship, the longitudinal stress, σ_x, is the dominant component. There are, however, locations in which the shear component becomes important and under unusual circumstances the transverse component may, likewise, become important. A suitable procedure for estimating these other component stresses may be derived by considering the equations of static equilibrium of the element of plating (Figure 18.26). The static equilibrium conditions for a plate element subjected only to in-plane stress, that is, no plate bending, are:

$$\partial Nx / \partial x + \partial N / \partial s = 0 \qquad [33\text{-a}]$$

$$\partial Ns / \partial s + \partial N / \partial x = 0 \qquad [33\text{-b}]$$

In these equations, s, is the transverse coordinate measured on the surface of the section from the x-axis as shown in Figure 18.26.

For vessels without continuous longitudinal bulkheads

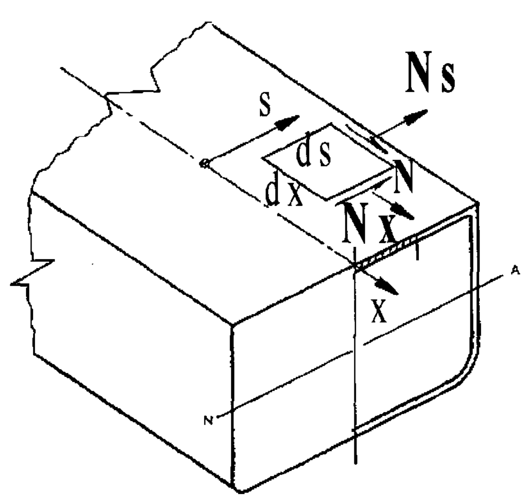

Figure 18.26 Shear Forces (2)

(*single cell*), having transverse symmetry and subject to a bending moment in the vertical plane, the shear flow distribution, N(s) is then given by:

$$N(s) = \left(\frac{V(x)}{I(x)}\right) m(s) \qquad [34]$$

and the shear stress, τ, at any point in the cross section is:

$$\tau(s) = \frac{V(x).m(s)}{t(s)\ I(x)} \quad (N / m^2) \qquad [35]$$

where:

V(x) = total shearing force (in N) in the hull for a given section x

$m(s) = \int_0^s t(s)\, z\, ds$, in m^3, is the first moment (or moment of area) about the neutral axis of the cross sectional area of the plating between the origin at the centerline and the variable location designated by s. This is the crosshatched area of the section shown in Figure 18.26

t(s) = thickness of material at the shear plane

I(x) = moment of inertia of the entire section

The total vertical shearing force, Vex), at any point, x, in the ship's length may be obtained by the integration of the load curve up to that point. Ordinarily the maximum value of the shearing force occurs at about one quarter of the vessel's length from either end.

Since only the vertical, or nearly vertical, members of the hull girder are capable of resisting vertical shear, this shear is taken almost entirely by the side shell, the continuous longitudinal bulkheads if present, and by the webs of any deep longitudinal girders.

The maximum value of't occurs in the vicinit~of the neutral axis, where the value of *t* is usually twice the thickness of the side plating (Figure 18.27). For vessels with continuous longitudinal bulkheads, the expression for shear stress is more complex.

Shear Flow in Multicell Sections: Ifthe cross section of the ship shown in Figure 18.28 is subdivided into two or more closed cells by longitudinal bulkheads, tank tops, or decks, the problem of finding the shear flow in the boundaries of these closed cells is statically indeterminate.

Equation 34 may be evaluated for the deck and bottom of the center tank space since the plane of symmetry at which the shear flow vanishes, lies within this space and forms a convenient origin for the integration. At the decklbulkhead intersection, the shear flow in the deck divides, but the relative proportions of the part in the bulkhead and the part in the deck are indeterminate. The sum of the shear flows at two locations lying on a plane cutting the cell walls will still be given by equation 34, with m(s) equal to the moment of the shaded area (Figure 1~.28). However, the distribution of this sum between the two components in bulkhead and side shell, requires additional information for its determination.

This additional information may be obtained by considering the torsional equilibrium and deflection of the cellular section. The way to proceed is extensively explained in Lewis (2).

18.4.3.3 Shear stress associated with torsion

In order to develop the twisting equations, we consider a closed, single cell, thin-walled prismatic section subject only to a twisting moment, Mp which is constant along the length as shown in Figure 18.29. The resulting shear stress may be assumed uniform through the plate thickness and is tangent to the mid-thickness of the material. Under these circumstances, the deflection of the tube will consist of a twisting of the section without distortion of its shape, and the rate of twist, d8/dx, will be constant along the length.

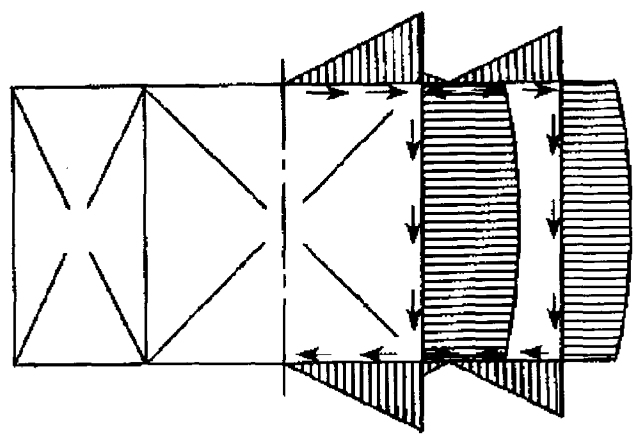

Figure 18.27 Shear Flow in Multicell Sections (1)

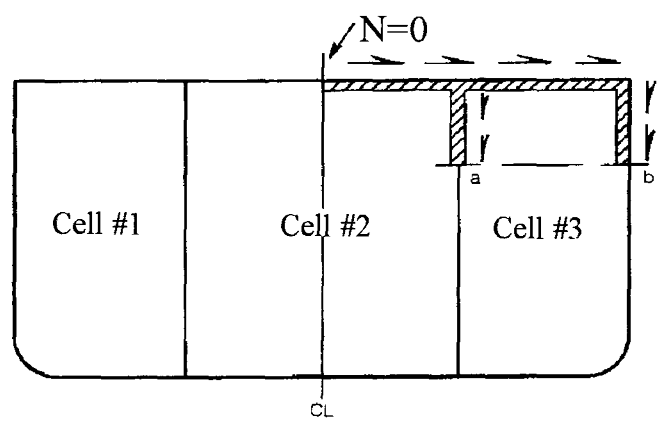

Figure 18.28 Shear Flow in Multicell Sections (2)

Now consider equilibrium of forces in the *x-direction* for the element dX.ds of the tube wall as shown in Figure 18.29. Since there is no longitudinal load, there will be no longitudinal stress, and only the shear stresses at the top and bottom edges need be considered in the expression for static equilibrium. The shear flow, N = τt, is therefore seen to be constant around the section.

The magnitude of the moment, *MT'* may be computed by integrating the moment of the elementary force arising from this shear flow about any convenient axis. If *r* is the distance from the axis, 0, perpendicular to the resultant shear flow at location s:

$$M_T = \oint r\, N\, ds = N \oint r\, ds = 2N\Omega \qquad [36]$$

Here the symbol indicates that the integral is taken entirely around the section and, therefore, Ω (m^2) is the area enclosed by the mid-thickness line of the tubular cross section. The constant shear flow, N (N/m), is then related to the applied twisting moment by:

$$N = \tau .\, t = M_T/2\Omega \qquad [37]$$

For uniform torsion of a closed prismatic section, the angle of torsion is:

$$\theta = \frac{M_T . L}{G\, I_p} \quad \text{(in radians)} \qquad [38]$$

where:

M_T = Twisting moment (torsion), in N.m
L = Length of the girder, in m
I_p = Polar Inertia, in m^4
G = E/2(1+ν), the shear Modulus, in N/m^2

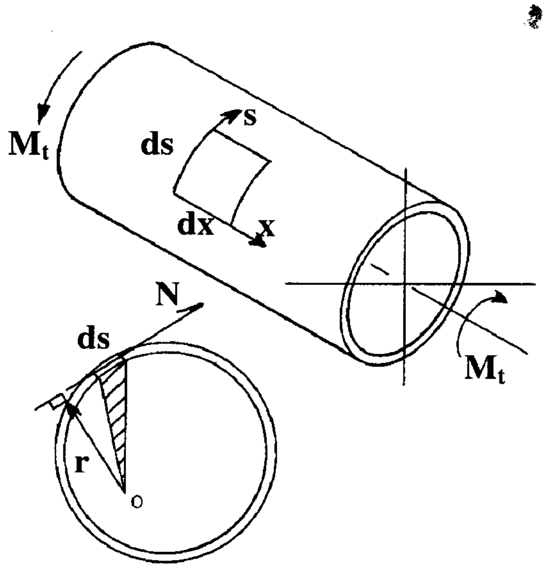

Figure 18.29 Torsional Shear Flow (2).

18.4.3.4 Twisting and warping

Torsional strength: Although torsion is not usually an important factor in ship design for most ships, it does"result in significant additional stresses on ships, such as container ships, which have large hatch openings. These warping stresses can be calculated by a beam analysis, which takes into account the twisting and warping deflections. There can also be an interaction between horizontal bending and torsion of the hull girder. Wave actions tending to bend the hull in a horizontal plane also induce torsion because of the *open* cross section of the hull, which results in the shear center being below the bottom of the hull. Combined stresses due to vertical bending, horizontal bending and torsion must be calculated.

In order to increase the torsional rigidity of the containership cross sections, longitudinal and transverse closed box girders are introduced in the upper side and deck structure.

From previous studies, it has been established that special attention should be paid to the torsional rigidity distribution along the hull. Usually, toward the ship's ends, the section moduli are justifiably reduced base on bending. On the contrary the torsional rigidity, especially in the forward hatches, should be gradually increased to keep the warping stress as small as possible.

Twisting of opened section: A lateral seaway could induce severe twisting moment that is of the major importance for ships having large deck openings. The equations for the twist of a closed tube (equations 36 to 38) are applicable only to the computation of the torsional response of closed thin-walled sections.

The relative torsional stiffness of closed and open sections may be visualized by means of a very simple example.

Consider two circular tubes, one of which has a longitudinal slit over its full length as in Figure 18.30. The closed tube will be able to resist a much greater torque per unit angular deflection than the open tube because of the inability of the latter to sustain the shear stress across the slot. The twisting resistance of the thin material of which the tube is composed provides the only resistance to torsion in the case

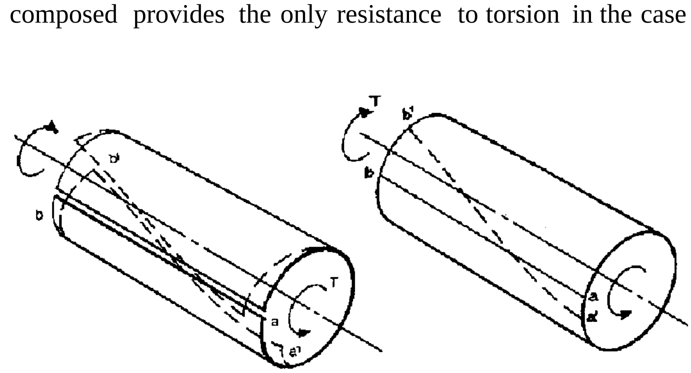

Figure 18.30 Twist of Open and Closed Tubes (2)

of the external loading applied and the boundary conditions along the plate edges, but not its thickness. Figure 18.33 gives the effective breadth ratio at mid-length for column loading and harmonic-shaped beam loading, together with a common approximation for both cases:

$$\frac{b_e}{b} = \frac{k}{6}\frac{L}{b} \qquad [40]$$

The results are presented in a series of design charts, which are especially simple to use, and may be found in Schade (26).

A real situation in which such an alternating load distribution may be encountered is a bulk carrier loaded with a dense ore cargo in alternate holds, the remainder being empty.

An example of the computation of the effective breadth of bottom and deck plating for such a vessel is given in Chapter VI of Taggart (1), using Figure 18.33.

It is important to distinguish the *effective breadth* (equation 40) and the *effective width* (equations 54 and 55) presented later in Subsection 18.6.3.2 for plate and stiffened plate-buckling analysis.

18.4.3.7 Longitudinal deflection

The longitudinal bending deflection of the ship girder is obtainable from the appropriate curvature equations (equations 27 and 28) by integrating twice. A semi-empirical approximation for bending deflection amidships is:

$$w = \alpha\,(M L^2/EI) \qquad [41]$$

where the dimensionless coefficient a. may be taken, for first approximation, as 0.09 (2).

Actual deflection in service is affected also by thermal influences, rigidity of structural components, and workmanship; furthermore, deflection due to shear is additive to the bending deflection, though its amount is usually relatively small.

The same influences, which gradually increase nominal design stress levels, also increase flexibility. Additionally, draft limitations and stability requirements may force the LID ratio up, as ships get larger. In general, therefore, modern design requires that more attention be focused on flexibility than formerly.

No specific limits on hull girder deflections are given in the classification rules. The required minimum scantlings however, as well as general design practices, are based on a limitation of the LID ratio range.

18.4.3.8 Load diffusion into structure

The description of the computation of vertical shear and bending moment by integration of the longitudinal load distribution implies that the external vertical load is resisted directly by the vertical shear carrying members of the hull girder such as the side shell or longitudinal bulkheads. In a longitudinally framed ship, such as a tanker, the bottom pressures are transferred principally to the widely spaced transverse web frames or the transverse bulkheads where

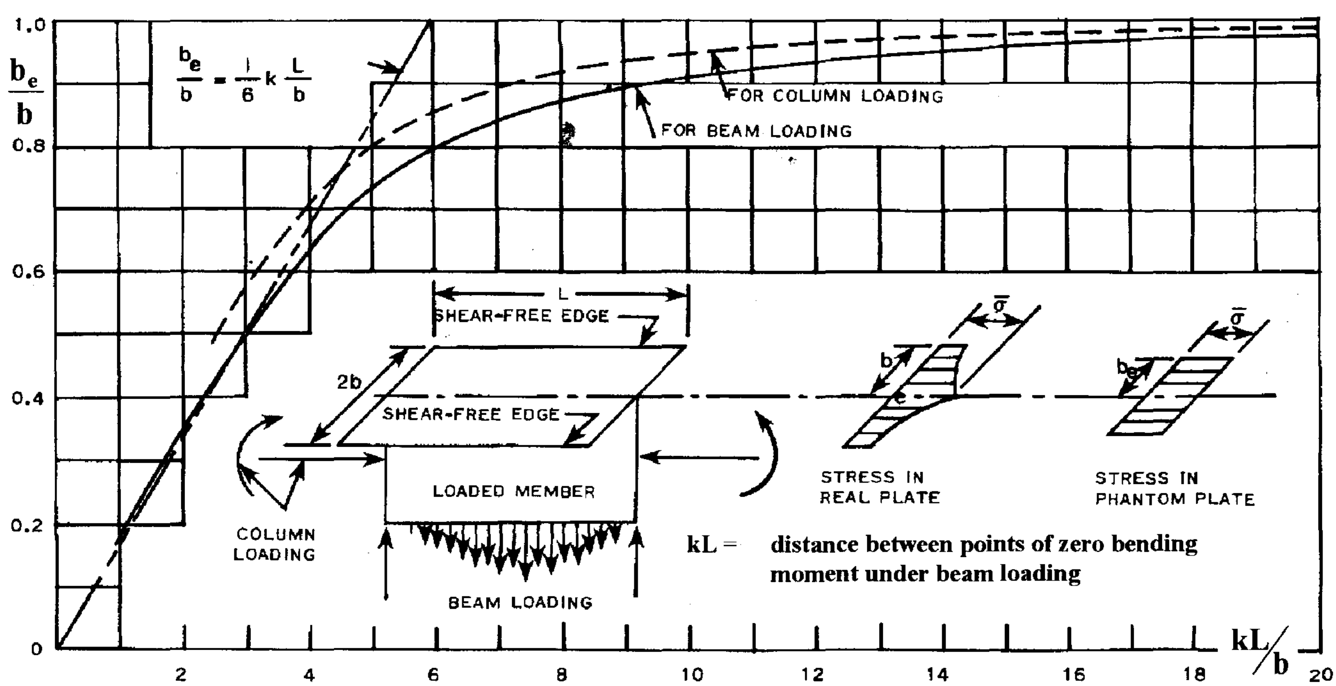

Figure 18.33 Effective Breath Ratios at Midlength (1)

they are transferred to the longitudinal bulkheads or side shell, again as localized shear forces. Thus, in reality, the loading q(x), applied to the side shell or the longitudinal bulkhead will consist of a distributed part due to the direct transfer of load into the member from the bottom or deck structure, plus a concentrated part at each bulkhead or web frame. This leads to a discontinuity in the shear curve at the bulkheads and webs.

18.4.3.9 Hull/superstructure interaction

The terms *superstructure* and *deckhouse* refer to a structure usually of shorter length than the entire ship and erected above the strength deck of the ship. If its sides are coplanar with the ship's sides it is referred to as a superstructure. If its width is less than that of the ship, it is called a deckhouse.

The prediction of the structural behavior of a superstructure constructed above the strength deck of the hull has facets involving both the general bending response and important localized effects. Two opposing schools of thought exist concerning the philosophy of design of such erections. One attempts to make the superstructure effective in contributing to the overall bending strength of the hull, the other purposely isolates the superstructure from the h~ll so that it carries only localized loads and does not experience stresses and deflections associated with bending of the main hull. This may be accomplished in long superstructures ($>0.5L_{pp}$) by cutting the deckhouse into short segments by means of expansion joints. Aluminum deckhouse construction is another alternative when the different material properties provide the required relief.

As the ship hull experiences a bending deflection in response to the wave bending moment, the superstructure is forced to bend also. However, the curvature of the superstructure may not necessarily be equal to th.atof th~ ~ll but depends upon the length of superstructure 10 relatlOt¥to the hull and the nature of the connection between the two, especially upon the vertical stiffness or *foundation modulus* of the deck upon which the superstructure is constructed. The behavior of the superstructure is similar to that of a beam on an elastic foundation loaded by a system of normal forces and shear forces at the bond to the hull.

The stress distributions at the midlength of the superstructure and the differential deflection between deckhouse and hull for three different degrees of superstructure effectiveness are shown on Figure 18.34.

The areas and inertias can be computed to account for shear lag in decks and bottoms. If the erection material differs from that of the hull (aluminum on steel, for example) the geometric erection area Af and inertia If must be reduced according to the ratio of the respective material moduli; that is, by multiplying by E (aluminum)/E (steel) (approximately one-third). Further details on the design considerations for deckhouses and superstructures may be found in Evans (27) and Taggart (1).

In addition to the overall bending, local stress concentrations may be expected at the ends of the house, since here the structure is transformed abruptly from that of a beam consisting of the main hull alone to that of hull plus superstructure.

Recent works achieved in Norwegian University of Science & Technology have shown that the vertical stress distribution in the side shell is not linear when there are large openings in the side shell as it is currently the case for upper decks of passenger vessels. Approximated stress distributions are presented at Figure 18.35. The reduced slope, e, for the upper deck has been found equal to 0.50 for a catamaran passenger vessel (28).

18.4.4 Secondary Response

In the case of secondary structural response, the principal objective is to determine the distribution of both in-plane

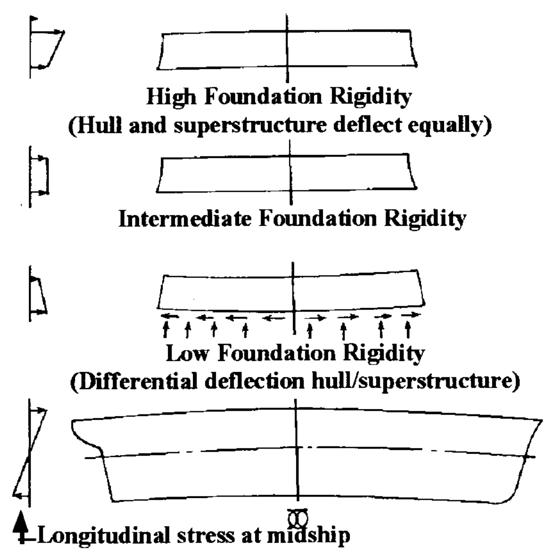

Figure 18.34 Three Interaction Levels between Superstructure and Hull (1)

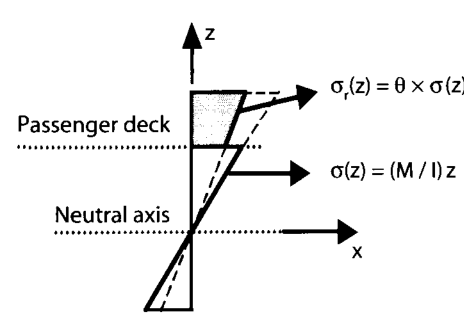

Figure 18.35 Vertical Stress Distribution in Passenger Vessels having Large Openings above the Passenger Deck

and normal loading, deflection and stress over the length and width dimensions of a stiffened panel. Remember that the primary response involves the determination of only the in-plane load, deflection, and stress as they vary over the length of the ship. The secondary response, therefore, is seen to be a two-dimensional problem while the primary response is essentially one-dimensional in character.

18.4.4.1 Stiffened panels

A stiffened panel of structure, as used in the present context, usually consists of a flat plate surface with its attached stiffeners, transverse frames and/or girders (Figure 18.36). When the plating is absent the module is a grid or *grillage* of beam members only, rather than a *stiffened panel.*

In principle, the solution for the deflection and stress in the stiffened panel may be thought of as a solution for the response of a system of orthogonal intersecting beams.

A second type of interaction arises from the two-dimensional stress pattern in the plate, which may be thought of as forming a part of the flanges of the stiffeners. The plate contribution to the beam bending stiffness arises from the direct longitudinal stress in the plate adjacent to the stiffener, modified by the transverse stress effects, anci also from the shear stress in the plane of the plate. The maximum secondary stress may be found in the plate itself, but more frequently it is found in the free flanges of the stiffeners, since these flanges are at a greater distance than the plate member from the neutral axis of the combined plate-stiffener.

At least four different procedures have been employed for obtaining the structural behavior of stiffened plate panels under normal loading, each embodying certain simplifying assumptions: 1) *orthotropic plate theory,* 2) *beam-on-elastic-foundation theory,* 3) *grillage theory* (intersecting beams), and 4) *the finite element method* (FEM).

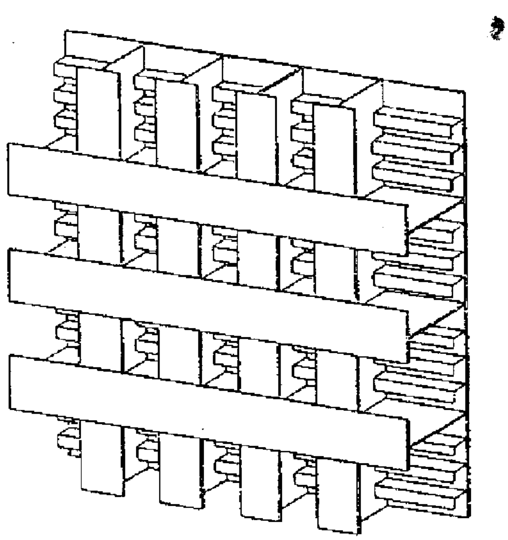

Figure 18.36 A Stiffened Panel with Uniformly Distributed Longitudinals, 4 Webframes, and 3 Girders.

Orthotropic plate theory refers to the theory of bending of plates having different flexural rigidities in the two orthogonal directions. In applying this theory to panels having discrete stiffeners, the structure is idealized by assuming that the structural properties of the stiffeners may be approximated by their average values, which are assumed to be distributed uniformly over the width or length of the plate. The deflections and stresses in the resulting continuum are then obtained from a solution of the orthotropic plate deflection differential equation:

$$a_1 \frac{\partial^4 w}{\partial x^4} + a_2 \frac{\partial^4 w}{\partial x^2 \partial y^2} + a_3 \frac{\partial^4 w}{\partial y^4} = p(x,y) \qquad [42]$$

where:

ai' ~, a_3 = express the average flexural rigidity of the orthotropic plate in the two directions

w(x,y) = is the deflection of the plate in the normal direction

p(x,y) = is the distributed normal pressure load per unit area

Note that the behavior of the isotropic plate, that is, one having uniform flexural properties in all directions, is a special case of the orthotropic plate problem. The orthotropic plate method is best suited to a panel in which the stiffeners are uniform in size and spacing and closely spaced. It has been said that the application of this theory to cross-stiffened panels must be restricted to stiffened panels with more than three stiffeners in each direction.

An advanced orthotropic procedure has been implemented by Rigo (29,30) into a computer-based scheme for the optimum structural design of the midship section. It is based on the differential equations of stiffened cylindrical shells (linear theory). Stiffened plates and cylindrical shells can both be considered, as plates are particular cases of the cylindrical shells having a very large radius. A system of three differential equations, similar to equation 42, is established (8th order coupled differential equations). Fourier series expansions are used to model the loads. Assuming that the displacements (u,v,w) can also be expanded in sin and cosine, an analytical solution ofu, v, and w(x,y) can be obtained for each stiffened panel.

This procedure can be applied globally to all the stiffened panels that compose a parallel section of a ship, typically a cargo hold.

This approach has three main advantages. First the plate bending behavior (w) and the inplane membrane behavior (u and v) are analyzed simultaneously. Then, in addition to the flexural rigidity (bending), the inplane axial, torsional, transverse shear and inplane shear rigidities of the stiffeners in the both directions can also be considered. Finally, the approach is suited for stiffeners uniform in size and spacing, and closely spaced but also for individual members, randomly distributed such as deck and bottom girders. These members considered through Heaviside functions that allow replacing each individual member by a set of 3 forces and 2 bending moment load lines. Figure 18.36 shows a typical stiffened panel that can be considered. It includes uniformly distributed longitudinals and web frames, and three prompt elements (girders).

The *beam on elastic foundation* solution is suitable for a panel in which the stiffeners are uniform and closely spaced in one direction and sparser in the other one. Each of these members is treated individually as a beam on an elastic foundation, for which the differential equation of deflection is,

$$EI\frac{\partial^4 w}{\partial x^4} + k\,w = q(x) \qquad [43]$$

where:

w = is the deflection
I = is sectional moment of inertia of the longitudinal stiffener, including adjacent plating.
k = is average spring constant per unit length of the transverse stiffeners
q(x) = is load per unit length on the longitudinal member

The *grillage approach* models the cross-stiffened panel as a system of discrete intersecting beams (in plane frame), each beam being composed of stiffener and associated effective plating. The torsional rigidity of the stiffened panel and the Poisson ratio effect are neglected. The validity of modeling the stiffened panel by an intersecting beam (w grillage) may be critical when the flexural rigidities of s'fiffeners are small compared to the plate stiffness. It is known that the grillage approach may be suitable when the ratio of the stiffener flexural rigidity to the plate bending rigidity (EIlbD with I the moment of inertia of stiffener and D the plate bending rigidity) is greater than 60 (31) otherwise if the bending rigidity of stiffener is smaller, an *Orthotropic Plate Theory* has to be selected.

The *FEM approach* is discussed in detail in section 18.7.2.

18.4.5 Tertiary Response

18.4.5.1 Unstiffened plate

Tertiary response refers to the bending stresses and deflections in the individual panels of plating that are bounded by the stiffeners of a secondary panel. In most cases the load that induces this response is a fluid pressure from either the water outside the ship or liquid or dry bulk cargo within. Such a loading is normal to and distributed over the surface of the panel. In many cases, the proportions, orientatioq, and location of the panel are such that the pressure may be assumed constant over its area.

As previously noted, the deflection response of an isotropic plate panel is obtained as the solution of a special case of the earlier orthotropic plate equation (equation 42), and is given by:

$$\frac{\partial^4 w}{\partial x^4} + 2\frac{\partial^4 w}{\partial x^2 \partial y^2} + \frac{\partial^4 w}{\partial y^4} = \frac{p(x,y)}{D} \qquad [44]$$

where:

$$D = \text{plate flexural rigidity} = \frac{E\,t^3}{12(1-\nu)}$$

t = the uniform plate thickness
p(x,y) = distributed unit pressure load

Appropriate boundary conditions are to be selected to represent the degree of fixity of the edges of the panel. Stresses and deflections are obtained by solving this equation for rectangular plates under a uniform pressure distribution. Equation 44 is in fact a simplified case of the general one (equation 42).

Information (including charts) on a plate subject to uniform load and concentrated load *(patch load)* is available in Hughes (3).

18.4.5.2 Local deflections

Local deflections must be kept at reasonable levels in order for the overall structure to have the proper strength and rigidity. Towards this end, the classification society rules may contain requirements to ensure that local deflections are not exceSSIve.

Special requirements also apply to stiffeners. Tripping brackets are provided to support the flanges, and they should be in line with or as near as practicable to the flanges of struts. Special attention must be given to rigidity of members under compressive loads to avoid buckling. This is done by providing a minimum moment of inertia at the stiffener and associated plating.

18.4.6 Transverse Strength

Transverse strength refers to the ability of the ship structure to resist those loads that tend to cause distortion of the cross section. When it is distorted into a parallelogram shape the effect is called *racking* (see Subsection 18.4.3.5). We recall that both the primary bending and torsional strength analyses are based upon the assumption of no distortion of the cross section. Thus, we see that there is an inherent relationship between transverse strength and both longitudinal and torsional strength. Certain structural members, including transverse bulkheads and deep web frames, must be incorporated into the ship in order to insure adequate transverse strength. These members provide support to and interact with longitudinal members by transferring loads from one part of a structure to another. For example, a portion of the bottom pressure loading on the hull is transferred via the center girder and the longitudinals to the transverse bulkheads at the ends of theses longitudinals. The bulkheads, in turn, transfer these loads as vertical shears into the side shell. Thus some of the loads acting on the transverse strength members are also the loads of concern in longitudinal strength considerations.

The general subject of transverse strength includes elements taken from both the primary and secondary strength categories. The loads that cause effects requiring transverse strength analysis may be of several different types, depending upon the type of ship, its structural arrangement, mode of operation, and upon environmental effects.

Typical situations requiring attention to the transverse strength are:

- ship out of water: on building ways or on construction or repair dry dock,
- tankers having empty wing tanks and full centerline tanks or VIce versa,
- ore carriers having loaded centerline holds and large empty wing tanks,
- all types of ships: torsional and racking effects caused by asymmetric motions of roll, sway and yaw, and
- ships with structural features having particular sensitivity to transverse effects, as for instance, ships having largely open interior structure (minimum transverse bulkheads) such as auto carriers, containers and RO-Jt) ships.

As previously noted, the transverse structural response involves pronounced interaction between transverse and longitudinal structural members. The principal loading consists of the water pressure distribution around the ship, and the weights and inertias of the structure and hold contents. As a first approximation, the transverse response of such a frame may be analyzed by a two-dimensional frame response procedure that mayor may not allow for support by longitudinal structure. Such analysis can be easily performed using 2D finite element analysis (FEA). Influence of longitudinal girders on the frame would be represented by elastic attachments having finite spring constants (similar to equation 43). Unfortunately, such a procedure is very sensitive to the spring location and the boundary conditions. For this reason, a three-dimensional analysis is usually performed in order to obtain results that are useful for more than comparative purposes. Ideally, the entire ship hull or at least a limited hold-model should be modeled. See Subsection 18.7.2-Structural Finite Element Models (Figure 18.57).

18.4.7 Superposition of Stresses

In plating, each response induces longitudinal stresses, transverse stresses and shear stresses. These stresses can be calculated individually for each response. This is the traditional way followed by the classification societies. With direct analysis such as finite element analysis (Subsection 18.7.2), it is not always possible to separate the different responses.

If calculated individually, all the longitudinal stresses have to be added. Similar cumulative procedure must be achieved for the transverse stresses and the shear stresses. At the end they are combined through a criteria, which is usually for ship structure, the von-Mises criteria (equation 45).

The standard procedure used by classification societies considers that longitudinal stresses induced by primary response of the hull girder, can be assessed separately from the other stresses. Classification rules impose through allowable stress and minimal section modulus, a maximum longitudinal stress induced by the hull girder bending moment.

On the other hand, they recommend to combined stresses from secondary response and tertiary response, in plating and in members. These are combined through the von Mises criteria and compared to the classification requirements.

Such an uncoupled procedure is convenient to use but does not reflect reality. Direct analysis does not follow this approach. All the stresses, from the primary, secondary and tertiary responses are combined for yielding assessment. For buckling assessment, the tertiary response is discarded, as it does not induce in-plane stresses. Nevertheless the lateralload can be considered in the buckling formulation (Subsection 18.6.3). Tertiary stresses should be added for fatigue analysis.

Since all the methods of calculation of primary, secondary, and tertiary stress presuppose linear elastic behavior of the structural material, the stress intensities computed for the same member may be superimposed in order to obtain a maximum value for the combined stress. In performing and interpreting such a linear superposition, several considerations affecting the accuracy and significance of the resulting stress values must be borne in mind.

First, the loads and theoretical procedures used in computing the stress components may not be of the same accuracy or reliability. The primary loading, for example, may be obtained using a theory that involves certain simplifications in the hydrodynamics of ship and wave motion, and the primary bending stress may be computed by simple beam theory, which gives a reasonably good estimate of the mean stress in deck or bottom but neglects certain localized effects such as shear lag or stress concentrations.

Second, the three stress components may not necessarily occur at the same instant in time as the ship moves through waves. The maximum bending moment amidships, which results in the maximum primary stress, does not necessarily occur in phase with the maximum local pressure on a midship panel of bottom structure (secondary stress) or panel of plating (tertiary stress).

Third, the maximum values of primary, secondary, and tertiary stress are not necessarily in the same direction or even in the same part of the structure. In order to visualize this, consider a panel of bottom structure with longitudinal framing. The forward and after boundaries of the panel will be at transverse bulkheads. The primary stress (σ_1) will act in the longitudinal direction, as given by equation 29. It will be nearly equal in the plating and the stiffeners, and will be approximately constant over the length of a mid ship panel. There will be a small transverse component in the plating, due to the Poison coefficient, and a shear stress given by equation 35. The secondary stress will probably be greater in the free flanges of the stiffeners than in the plating, since the combined neutral axis of the stiffener/plate combination is usually near the plate-stiffener joint. Secondary stresses, which vary over the length of the panel, are usually subdivided into two parts in the case of single hull structure. The first part (σ_2) is associated with bending of a panel of structure bounded by transverse bulkheads and either the side shell or the longitudinal bulkheads. The principal stiffeners, in this case, are the center and any side longitudinal girders, and the transverse web frames. The secor; part, (σ_2*), is the stress resulting from the bending of the smaller panel of plating plus longitudinal stiffeners that is bounded by the deep web frames. The first of these components (σ_2), as a result of the proportions of the panels of structure, is usually larger in the transverse than in the longitudinal direction. The second (σ_2*) is predominantly longitudinal. The maximum tertiary stress (σ_3) happens, of course, in the plate where biaxial stresses occur. In the case of longitudinal stiffeners, the maximum panel tertiary stress will act in the transverse direction (normal to the framing system) at the mid-length of a long side.

In certain cases, there will be an appreciable shear stress component present in the plate, and the proper interpretation and assessment of the stress level will require the resolution of the stress pattern into principal stress components.

From all these considerations, it is evident that, in many cases, the point in the structure having the highest stress level will not always be immediately obvious, but must be found by considering the combined stress effects at a number of different locations and times.

The nominal stresses produced from the analysis will be a combination of the stress components shown in Figures 18.21 and 18.37.

18.4.7.1 van Mises equivalent stress

The yield strength of the material, σ_{yield} is defined as the measured stress at which appreciable nonlinear behavior accompanied by permanent plastic deformation of the material occurs. The ultimate strength is the highest level of stress achieved before the test specimen fractures. For most shipbuilding steels, the yield and tensile strengths in tension and compression are assumed equal.

The stress criterion that must be used is one in which it is possible to compare the actual multi-axial stress with the material strength expressed in terms of a single value for the yield or ultimate stress.

For this purpose, there are several theories of material failure in use. The one usually considered the most suitable for ductile materials such as ship steel is referred to as the *von Mises Theory:*

$$\sigma_e = \left(\sigma_x^2 + \sigma_y^2 - \sigma_x \sigma_y + 3\tau^2\right)^{1/2} \qquad [45]$$

Consider a plane stress field in which the component stresses are σ_x, σ_y and τ. The distortion energy states that

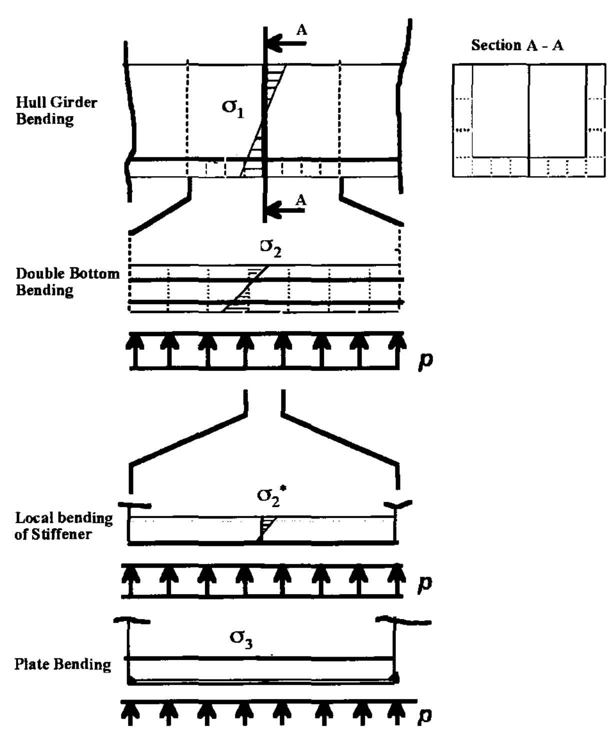

Figure 18.37 Definition of Stress Components (4)

failure through yielding will occur if the equivalent von Mises stress, σ_e, given by equation 45 exceeds the equivalent stress, σ_o, corresponding to yielding of the material test specimen. The material yield strength may also be expressed through an equivalent stress at failure: $\sigma_0 = \sigma_{yield} (= \sigma_Y)$.

18.4.7.2 Permissible stresses (Yielding)

In actual service, a ship may be subjected to bending in the inclined position and to other forces, such as those, which induce torsion or side bending in the hull girder, not to mention the dynamic effects resulting from the motions of the ship itself. Heretofore it has been difficult to arrive at the minimum scantlings for a large ship's hull by first principles alone, since the forces that the structure might be required to withstand in service conditions are uncertain. Accordingly, it must be assumed that the allowable stress includes an adequate factor of safety, or margin, for these uncertain loading factors.

In practice, the margin against yield failure of the structure is obtained by a comparison of the structure's von Mises equivalent stress, σ_e, against the permissible stress (or allowable stress), σ_0, giving the result:

$$\sigma_e \leq \sigma_0 = s_1 \times \sigma_Y \qquad [46]$$

where:

s_1 = partial safety factor defined by classification societies, which depends on the loading conditions and method of analysis. For 20 years North Atlantic conditions (seagoing condition), the s_1 factor is usually taken between 0.85 and 0.95

σ_Y = minimum yield point of the considered steel (mild steel, high tensile steel, etc.)

For special ship types, different permissible stresses may be specified for different parts of the hull structure. For example, for LNG carriers, there are special strain requirements in way of the bonds for the containment system, which in turn can be expressed as equivalent stress requirements.

For local areas subjected to many cycles of load reversal, fatigue life must be calculated and a reduced permissible stress may be imposed to prevent fatigue failure (see Subsection 18.6.6).

18.5 LIMIT STATES AND FAILURE MODES

Avoidance of structural failure is the goal of all structural designers, and to achieve this goal it is necessary for the designer to be aware of the potential limit states, failure modes and methods of predicting their occurrence. This section presents the basic types of failure modes and associated limit states. A more elaborate description of the failure modes and methods to assess the structural capabilities in relation to these failure modes is available in Subsection 18.6.1.

Classically, the different limit states were divided in 2 major categories: the *service limit state* and the *ultimate limit state.* Today, from the viewpoint of structural design, it seems more relevant to use for the steel structures four types of limit states, namely:

1. service or serviceability limit state,
2. ultimate limit state,
3. fatigue limit state, and
4. accidental limit state.

This classification has recently been adopted by ISO.

A *service limit state* corresponds to the situation where the structure can no longer provide the service for which it was conceived, for example: excessive deck deflection, elastic buckling in a plate, and local cracking due to fatigue. Typically they relate to aesthetic, functional or maintenance problem, but do not lead to collapse.

An *ultimate limit state* corresponds to collapse/failure, including collision and grounding. A classic example of ultimate limit state is the ultimate hull bending moment (Figure 18.46). The ultimate limit state is symbolized by the higher point (C) of the moment-curvature curve (M-cI».

Fatigue can be either considered as a third limit state or, classically, considered as a service limit state. Even if it is also a matter of discussion, *yielding* should be considered as a service limit state. First yield is sometimes used to assess the ultimate state, for instance for the ultimate hull bending moment, but basically, collapse occurs later. Most of the time, *vibration* relates to service limit states.

In practice, it is important to differentiate *service, ultimate,fatigue* and *acddentallimit states* because the partial safety factors associated with these limit states are generally different.

18.5.1 Basic Types of Failure Modes

Ship structural failure may occur as a result of a variety of causes, and the degree or severity of the failure may vary from a minor esthetic degradation to catastrophic failure resulting in loss of the ship. Three major failure modes are defined:

1. tensile or compressive yield of the material (plasticity),
2. compressive instability (buckling), and
3. fracture that includes ductile tensile rupture, low-cycle fatigue and brittle fracture.

Yield occurs when the stress in a structural member exceeds a level that results in a permanent plastic deformation of the material of which the member is constructed. This stress level is termed the material *yield stress.* At a somewhat higher stress, termed the *ultimate stress,* fracture of the material occurs. While many structural design criteria are based upon the prevention of any yield whatsoever, it should be observed that localized yield in some portions of a structure is acceptable. Yield must be considered as a serviceability limit state.

Instability and *buckling* failure of a structural member loaded in compression may occur at a stress level that is substantially lower than the material yield stress. The load at which instability or buckling occurs is a function of member geometry and material elasticity modulus, that is, slenderness, rather than material strength. The most common example of an instability failure is the buckling of a simple column under a compressive load that equals or exceeds the *Euler Critical Load.* A plate in compression also will have a critical buckling load whose value depends on the plate thickness, lateral dimensions, edge support conditions and material elasticity modulus. In contrast to the column, however, exceeding this load by a small margin will not necessarily result in complete collapse of the plate but only in an elastic deflection of the central portion of the plate away from its initial plane. After removal of the load, the plate may return to its original un-deformed configuration (for elastic buckling). The ultimate load that may be carried by a buckled plate is determined by the onset of yielding at some point in the plate material or in the stiffeners, in the case of a stiffened panel. Once begun, yield may propagate rapidly throughout the entire plate or stiffened panel with further increase in load.

Fatigue failure occurs as a result of a cumulative effect in a structural member that is exposed to a stress pattern alternating from tension to compression through ma1J' cycles. Conceptually, each cycle of stress causes some small but irreversible damage within the material and, after the accumulation of enough such damage, the ability of the member to withstand loading is reduced below the level of the applied load. Two categories of fatigue damage are generally recognized and they are termed *high-cycle* and *low-cycle* fatigue. In high-cycle fatigue, failure is initiated in the form of small cracks, which grow slowly and which may often be detected and repaired before the structure is endangered. High-cycle fatigue involves several millions of cycles of relatively low stress (less than yield) and is typically encountered in machine parts rotating at high speed or in structural components exposed to severe and prolonged vibration. Low-cycle fatigue involves higher stress levels, up to and beyond yield, which may result in cracks being initiated after several thousand cycles.

The loading environment that is typical of ships and ocean structures is of such a nature that the cyclical stresses may be of a relatively low level during the greater part of the time, with occasional periods of very high stress levels caused by storms. Exposure to such load conditions may result in the occurrence of low-cycle fatigue cracks after an interval of a few years. These cracks may grow to serious size if they are not detected and repaired.

Concerning *brittle fracture,* small cracks suddenly begin to grow and travel almost explosively through a major portion of the structure. The term *brittle fracture* refers to the fact that below a certain temperature, the ultimate tensile strength of steel diminishes sharply (lower impact energy). The originating crack is usually found to have started as a result of poor design or manufacturing practice. Fatigue (Subsection 18.6.6) is often found to play an important role in the initiation and early growth of such originating cracks. The prevention of brittle fracture is largely a matter of material selection and proper attention to the design of structural details in order to avoid stress concentrations. The control of brittle fracture involves a combination of design and inspection standards aimed toward the prevention of stress concentrations, and the selection of steels having a high degree of notch toughness, especially at low temperatures. Quality control during construction and in-service inspection form key elements in a program of fracture control.

In addition to these three failure modes, additional modes are:

- collision and grounding, and
- vibration and noise.

Collision and *Grounding* is discussed in Subsection 18.6.7 and *Vibration* in Subsection 18.6.8. Vibration as well as noise is not a failure mode, while it could fall into the serviceability limit state.

18.6 ASSESSMENT OF STRUCTURAL CAPACITY

18.6.1 Failure Modes Classification

The types of failure that may occur in ship structures are generally those that are characteristic of structures made up of stiffened panels assembled through welding. Figure 18.38 presents the different structure levels: the *global structure,* usually a cargo hold (Level 1), the *orthotropic stiffened panel* or *grillage* (Level 2) and the *inteiframe longitudinally stiffened panel* (Level 3) or its simplified modeling: the *beam-column* (LeveI3b). Level 4 (Figure 18.44a) is the *unstiffened plate* between two longitudinals and two transverse frames (also called bare plate).

The word *grillage* should be reserve to a structure composed of a grid of beams (without attached plating). When the grid is fixed on a plate, *orthotropic stiffened panel* seems to the authors more adequate to define a panel that is orthogonally stiffened, and having thus orthotropic properties.

The relations between the different failure modes and structure levels can be summarized as follows:

- *Level 1:* Ultimate bending moment, M_u, of the global structure (Figure 18.46).
- *Level 2:* Ultimate strength of compressed orthotropic stiffened panels (σ_u),

$$\sigma_u = \min\,[\sigma_u\,(\text{mode i})],\ i = I \text{ to } VI,$$

the 6 considered failure modes.

- *Level* 3:
  Mode I: Overall buckling collapse (Figure l8.44d),
  Mode II: Plate/Stiffener Yielding
  Mode III: Pull of interframe panels with a plate-stif ener combination (Figure l8.44b) using a *beam-column model* (Leve13b) or an *orthotropic model* (Level 3), considering:
  - plate induced failure (buckling)
  - stiffener induced failure (buckling or yielding)
  Mode IV and V: Instability of stiffeners (local buckling, tripping-Figure 18.44c)
  Mode VI: Gross Yielding
- *Level* 4: Buckling collapse of unstiffened plate (bare plate, Figure 18.44a).

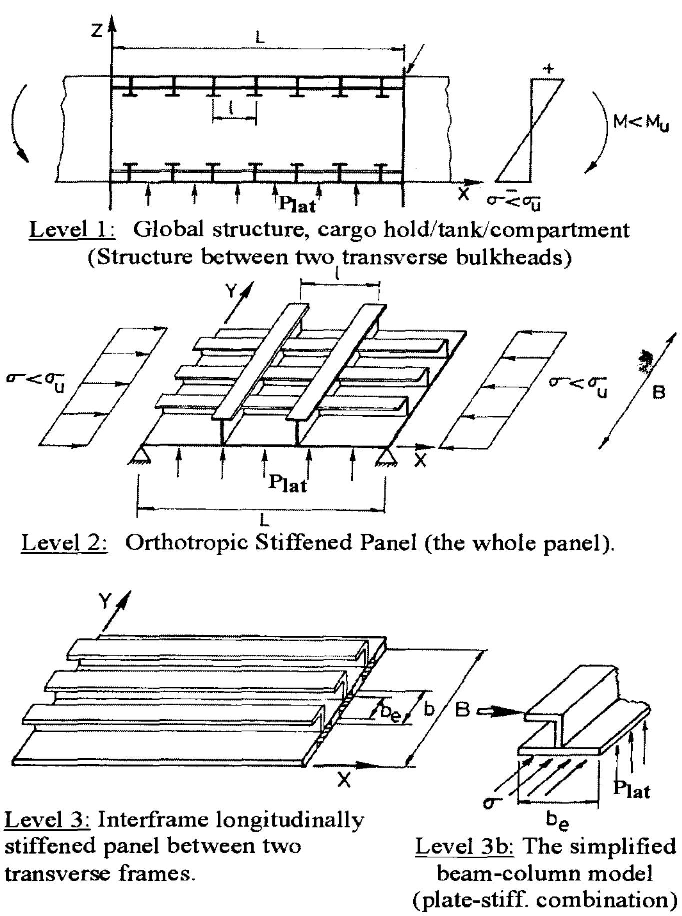

Figure 18.38 Structural Modeling of the Structure and its Components

To avoid collapse related to the Mode *I*, a minimal rigidity is generally imposed for the transverse frames so that an interframe panel collapse (Mode *II/)* always occurs prior to overall buckling (Mode /). It is a *simple* and *easy* constraint to implement, thus avoiding any complex calculation of overall buckling (mode /).

Note that the failure Mode *///* is influenced by the buckling of the bare plate (elementary unstiffened plate). Elastic buckling of theses unstiffened plates is usually not considered as an *ultimate limit state* (failure mode), but rather as a *service limit state.* Nevertheless, plate buckling (Level 4) may significantly affect the ultimate strength of the stiffened panel (Level 3).

Sources of the failures associated with the *serviceability* or *ultimate limit states* can be classified as follows:

18.6.1.1 Stiffened panel failure modes

Service limit state

- upper and lower bounds (Xmin~SX:::;Xmax):plate thickness, dimensions of longitudinals and transverse stiffeners (web, flange and spacing).
- maximum allowable stresses against first yield (Subsection 18.4.7)
- panel and plate deflections (Subsections 18.4.4.1 and 18.4.5.2), and defleotion of support members.
- elastic buckling of unstiffened plates between two longitudinals and two transverse stiffeners, frames or bulkheads (Subsection 18.6.3),
- local elastic buckling of longitudinal stiffeners (web and flange). Often the stiffener web/flange buckling does not induce immediate collapse of the stiffened panel as tripping does. It could therefore be considered as a *serviceability ultimate limit state.* However, this failure mode could also be classified into the *ultimate limit state* since the plating may sometimes remain without stiffening once the stiffener web buckles.
- vibration (Sub-ection 18.6.8)
- fatigue (Sub-ection 18.6.6)

Ultimate limit state (Subsection 18.6.4).

- overall collapse of orthotropic panels (entire stiffened plate structure),

- collapse of interframe longitudinally stiffened panel, including torsional-flexural (lateral-torsional) buckling of stiffeners (also called tripping).

18.6.1.2 Frame failure modes

Service limit state (Subsection 18.4.6).

- Upper and lower bounds ($X_{min} \leq X \leq X_{max}$),
- Minimal rigidity to guarantee rigid supports to the interframe panels (between two transverse frames).
- Allowable stresses under the resultant forces (bending, shear, torsion)

  — Elastic analysis,
  — Elasto-plastic analysis.

- Fatigue (Subsection 18.6.6)

Ultimate limit state

- Frame bucklings: These failures modes are considered as ultimate limit states rather than a service limit state. If one of them appears, the assumption of rigid supports is no longer valid and the entire stiffened panel can reach the ultimate limit state ..

  - Buckling of the compressed members,
  - Local buckling (web, flange).

18.6.1.3 Hull girder collapse modes

Service limit state

- Allowable stresses and first yield (Subsection 18.4.3.1),
- Deflection of the global structure and relative deflections of components and panels (Subsection 18.4.3.7).

*Ultimate limit state*t

- Global ultimate strength (ofthe hull girder/box girder). This can be done by considering an entire cargo hold or only the part between two transverse web frames (Subsection 18.6.5). Collapse of frames is assumed to only appear after the collapse of panels located between these frames. This means that it is sufficient to verify the box girder ultimate strength between two frames to be protected against a more general collapse including, for instance, one or more frame spans. This approach can be un-conservative if the frames are not stiff enough.
- Collision and grounding (Subsection 18.6.7), which is in fact an *accidental limit state.*

A relevant comparative list of the limit states was defined by the Ship Structure Committee Report No 375 (32) (see also reference 32).

18.6.2 Yielding

As explained in Subsection 18.5.1 yield occurs when the stress in a structural component exceeds the *yield stress.*

It is necessary to distinguish between first yield state and fully plastic state. In bending, first yield corresponds to the situation when stress in the extreme fiber reaches the yield stress. If the bending moment continues to increase the yield area is growing. The final stage corresponds to the Plastic Moment (~), where, both the compression and tensile sides are fully yielded (as shown on Figure 18.47).

Yield can be assessed using basic bending theory, equation 29, up to complex 3D nonlinear FE analysis. Design criteria related to first yield is the von Mises equivalent stress (equation 45).

Yielding is discussed in detail in Section 18.4.

18.6.3 Buckling and Ultimate Strength of Plates

A ship stiffened plate structure can become unstable if either buckling or collapse occurs and may thus fail to perform its function. Hence plate design needs to be such that instability under the normal operation is prevented (Figure 18.44a). The phenomenon of buckling is normally divided into three categories, namely elastic buckling, elastic-plastic buckling and plastic buckling, the last two being called inelastic buckling. Unlike columns, thin plating buckled in the elastic regime may still be stable since it can normally sustain further loading until the ultimate strength is reached, even if the in-plane stiffness significantly decreases after the inception of buckling. In this regard, the elastic buckling of plating between stiffeners may be allowed in the design, sometimes intentionally in order to save weight. Since significant residual strength of the plating is not expected after buckling occurs in the inelastic regime, however, inelastic buckling is normally considered to be the ultimate strength of the plate.

The buckling and ultimate strength of the structure depends on a variety of influential factors, namely geometric/material properties, loading characteristics, fabrication related imperfections, boundary conditions and local damage related to corrosion, fatigue cracking and denting.

18.6.3.1 Direct analysis

In estimating the load-carrying capacity of plating between stiffeners, it is usually assumed that the stiffeners are stable and fail only after the plating. This means that the stiffeners should be designed with proper proportions that help attain such behavior. Thus, webs, faceplates and flanges of the stiffeners or support members have to be proportioned so that local instability is prevented prior to the failure of plating.

Four load components, namely longitudinal compression/tension, transverse compression/tension, edge shear and lateral pressure loads, are typically considered to act on ship plating between stiffeners, as shown in Figure 18.39, while the in-plane bending effects on plate buckling are also sometimes accounted for. In actual ship structures, lateral pressure loading arises from water pressure and cargo weight. The still water magnitude of water pressure depends on the vessel draft, and the still water value of cargo pressure is determined by the amount and density of cargo loaded.

These still water pressure values may be augmented by wave action and vessel motion. Typically the larger in-plane loads are caused by longitudinal hull girder bending, both in still water and in waves at sea, which is the source of the primary stress as previously noted in Subsection 18.4.3.

The *elastic plate buckling strength* components under single types of loads, that is, σ_{xE} for σ_{xav}, σ_{yE} for σ_{yav} and τ_E for τ_{av}, can be calculated by taking into account the related effects arising from in-plane bending, lateral pressure, cut-outs, edge conditions and welding induced residual stresses.

The *critical (elastic-plastic) buckling strength* components under single types of loads, that is, σ_{xB} for σ_{xav}, σ_{yB} for σ_{yav} and τ_B for τ_{av}, are typically calculated by plasticity correction of the corresponding elastic buckling strength using the Johnson-Ostenfeld formula, namely:

$$\sigma_B = \begin{cases} \sigma_E & \text{for } \sigma_E \le 0.5\sigma_F \\ \sigma_F\left(1 - \dfrac{\sigma_F}{4\sigma_E}\right) & \text{for } \sigma_E > 0.5\sigma_F \end{cases} \qquad [47]$$

where:

σ_E = elastic plate buckling strength

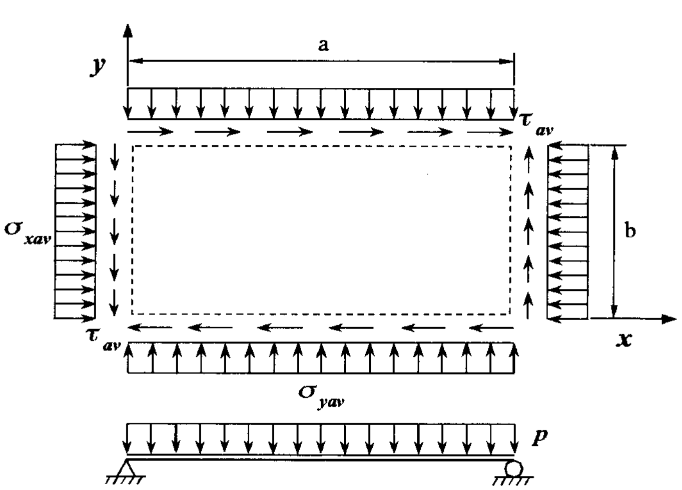

Figure 18.39 A Simply Supported Rectangular Plate Subject to Biaxial Compression/tension, Edge Shear and Lateral Pressure Loads

σ_B = critical buckling strength (that is, τ_B for shear stress)
$\sigma_F = \sigma_Y$ for normal stress
$= \sigma_Y \sqrt{3}$ for shear stress
σ_Y = material yield stress

In ship rules and books, equation 47 may appear with somewhat different constants depending on the structural proportional limit assumed. The above form assumes a structural proportional limit of a half the applicable yield value.

For axial tensile loading, the *critical* strength may be considered to equal the material yield stress (σ_Y).

Under single types of loads, the critical plate buckling strength must be greater than the corresponding applied stress component with the relevant margin of safety. For combined biaxial compression/tension and edge shear, the following type of critical buckling strength interaction criterion would need to be satisfied, for example:

$$\left(\frac{\sigma_{xav}}{\sigma_{xB}}\right)^c - \alpha\frac{\sigma_{xav}}{\sigma_{xB}}\frac{\sigma_{yav}}{\sigma_{yB}} + \left(\frac{\sigma_{yav}}{\sigma_{yB}}\right)^c + \left(\frac{\tau_{av}}{\tau_B}\right)^c \le \eta_B \qquad [48]$$

where:

η_B = usage factor for buckling strength, which is typically the inverse of the conventional partial safety factor.
η_B = 1.0 is often taken for direct strength calculation, while it is taken less than 1.0 for practical design in accordance with classification society rules.

Compressive stress is taken as negative while tensile stress is taken as positive and $\alpha = 0$ if both σ_{xav} and σ_{yav} are compressive, and $\alpha = 1$ if either σ_{xav} or σ_{yav} or both are tensile. The constant c is often taken as c = 2.

Figure 18.40 shows a typical example of the axial membrane stress distribution inside a plate element under predominantly longitudinal compressive loading before and after buckling occurs. It is noted that the membrane stress distribution in the loading (x) direction can become non-uniform as the plate element deforms. The membrane stress distribution in the *y* direction may also become non-uniform with the unloaded plate edges remaining straight, while no membrane stresses will develop in the y direction if the unloaded plate edges are free to move in plane. As evident, the maximum compressive membrane stresses are developed around the plate edges that remain straight, while the minimum membrane stresses occur in the middle of the plate element where a membrane tension field is formed by the plate deflection since the plate edges remain straight.

With increase in the deflection of the plate keeping the edges straight, the upper and/or lower fibers inside the middle of the plate element will initially yield by the action of bending. However, as long as it is possible to redistribute

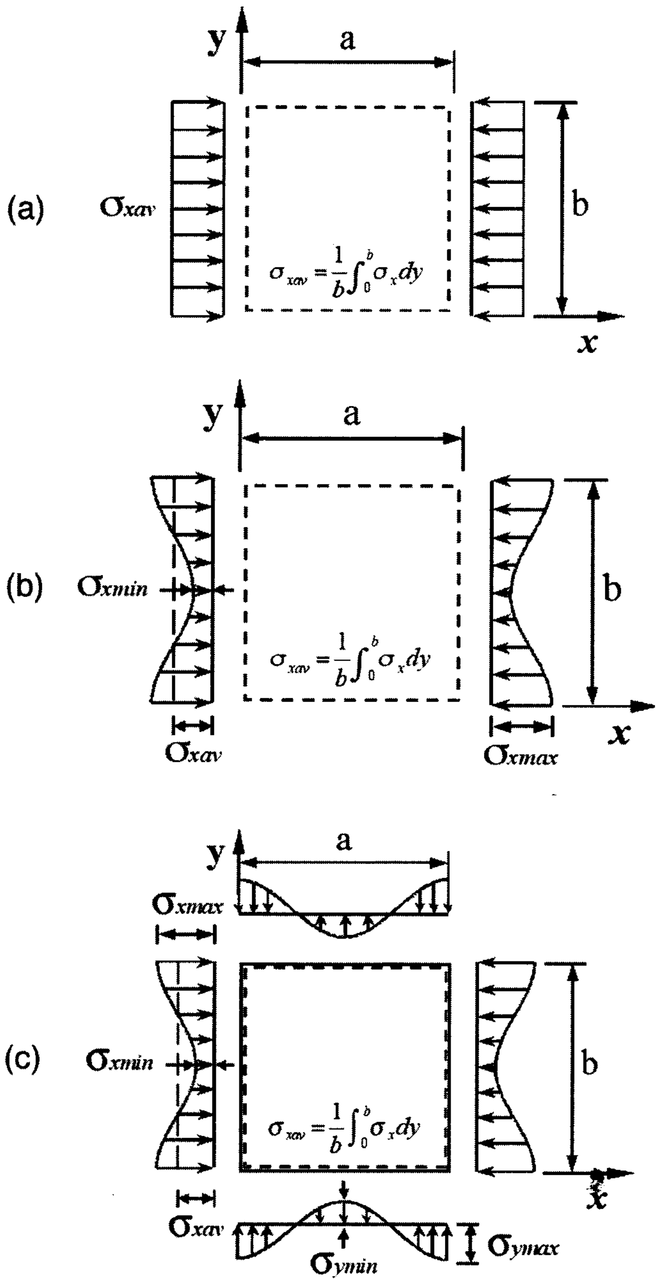

Figure 18.40 Membrane Stress Distribution Inside the Plate Element under Predomianntly Longitudinal Compressive Loads; (a) Before buckling, (b) After buckling, unloaded edges move freely in plane, (c) After buckling, unloaded edges kept straight

the applied loads to the straight plate boundaries by the membrane action, the plate element will not collapse. Collapse will then occur when the most stressed boundary locations yield, since the plate element can not keep the boundaries straight any further, resulting in a rapid increase of lateral plate deflection (33). Because of the nature of applied axial compressive loading, the possible yield loca-

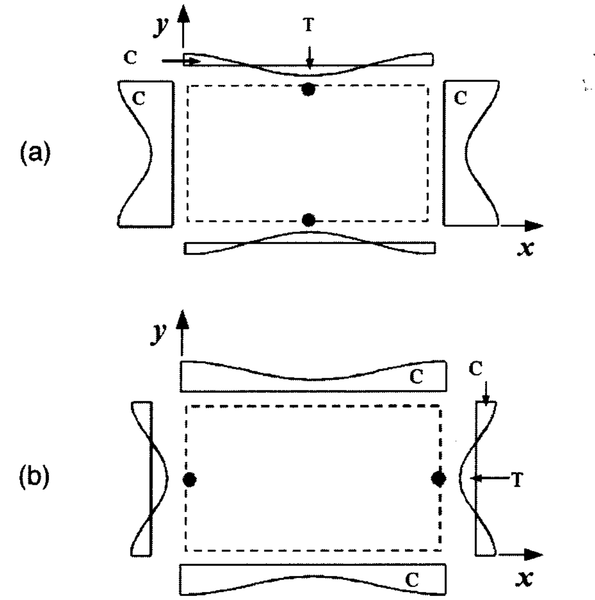

Figure 18.41 Possible Locations for the Initial Plastic Yield at the Plate Edges (Expected yield locations, T: Tension, C: Compression); (a) Yield at longitudinal mid-edges under longitudinal uniaxial compression, (b) Yield at transverse mid-edges under transverse uniaxial compression)

tions are longitudinal mid-edges for longitudinal uniaxial compressive loads and transverse mid-edges for transverse uniaxial compressive loads, as shown in Figure 18.41.

The occurrence of yielding can be assessed by using the von Mises yield criterion (equation 45). The following conditions for the most probable yield locations will then be found.

(a) Yielding at longitudinal edges:

$$\sigma_{x\,max}^2 - \sigma_{x\,max}\sigma_{y\,min} + \sigma_{y\,min}^2 = \sigma_Y^2 \qquad [49a]$$

(b) Yielding at transverse edges:

$$\sigma_{x\,min}^2 - \sigma_{x\,min}\sigma_{y\,max} + \sigma_{y\,max}^2 = \sigma_Y^2 \qquad [49b]$$

The maximum and minimum membrane stresses of equations 49a and 49b can be expressed in terms of applied stresses, lateral pressure loads and fabrication related initial imperfections, by solving the *nonlinear* governing differential equations of plating, based on equilibrium and compatibility equations. Note that equation 44 is the *linear* differential equation.

On the other hand, the plate ultimate edge shear strength, τ_u, is often taken $\tau_u = \tau_B$ (equation 47, with τ_B instead of σ_B). Also, an empirical formula obtained by curve fitting based on nonlinear finite element solutions may be utilized (33). The effect of lateral pressure loads on the plate ultimate edge shear strength may in some cases need to be accounted for.

For combined biaxial compression/tension, edge shear and lateral pressure loads, the last being usually regarded as a given constant secondary load, the plate ultimate strength interaction criterion may also be given by an expression similar to equation 48, but replacing the critical buckling strength components by the corresponding ultimate strength components, as follows:

$$\left(\frac{\sigma_{xav}}{\sigma_{xu}}\right)^c - \alpha\frac{\sigma_{xav}}{\sigma_{xu}}\frac{\sigma_{yav}}{\sigma_{yu}} + \left(\frac{\sigma_{yav}}{\sigma_{yu}}\right)^c + \left(\frac{\tau_{av}}{\tau_u}\right)^c \leq \eta_u \quad [50]$$

where:

α and c = variables defined in equation 48

η_u = usage factors for the ultimate limit state

σ_{xu} and σ_{yu} = solutions of equation 49a with regard to σ_{xav} and equation 49b with regard to σ_{yav}, respectively

18.6.3.2 Simplified models

In the interest of simplicity, the elastic plate buckling strength components under single types of loads may sometimes be calculated by neglecting the effects of in-plane bending or lateral pressure loads. Without considering the effect of lateral pressure, the resulting elastic buckling strength prediction would be pessimistic. While the plate edges are often supposed to be simply supported, that is, without rotational restraints along the plate/stiffener junctions, the real elastic buckling strength with rotational restraints would of course be increased by a certain percentages, particularly for heavy stiffeners. This arises from the increased torsional restraint provided at the plate edges in such cases.

The theoretical solution for critical buckling stress, σ_B, in the elastic range has been found for a number of cases of interest. For rectangular plate subject to compressive in-plane stress in one direction:

$$\sigma_B = k_c \frac{\pi^2 E}{12(1-\nu^2)}\left(\frac{t}{b}\right)^2 \quad [51]$$

Here k_c is a function of the plate aspect ratio, $\alpha = a/b$, the boundary conditions on the plate edges and the type of loading. If the load is applied uniformly to a pair of opposite edges only, and if all four edges are simply supported, then k_c is given by:

$$k_c = \left(\frac{m}{\alpha} + \frac{\alpha}{m}\right)^2 \quad [52]$$

where m is the number of half-waves of the deflected plate in the longitudinal direction, which is taken as an integer satisfying the condition $\alpha \leq \sqrt{m(m+1)}$. For long plate in

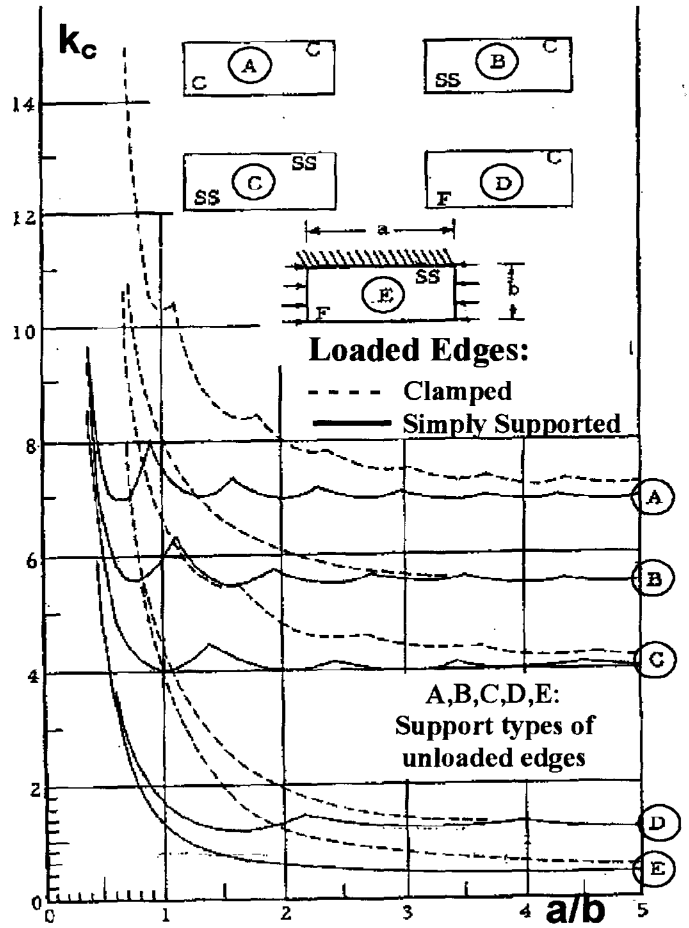

Figure 18.42 Compressive Buckling Coefficient for Plates in Compression; for 5 Configurations (A, B, C, D and E) where Boundary Conditions of Unloaded Edges are: SS: *Simply Supported*, C: *Clamped*, and F: *Free* (2)

compression (a > b), $k_c = 4$ and for wide plate ($a \leq b$) in compression, $k_c = (1 + b^2 / a^2)^2$, for simply supported edges.

For shear force, the critical buckling shear stress, τ_B, can also be obtain by equation 51 and the buckling coefficient for simply supported edges is:

$$kc = 5.34 + 4(b/a)^2 \quad [53]$$

Figure 18.42 presents, k_c, versus the aspect ratio, a/b, for different configurations of rectangular plates in compression.

For the *simplified prediction of the plate ultimate strength* under uniaxial compressive loads, one of the most common approaches is to assume that the plate will collapse if the maximum compressive stress at the plate corner reaches the material yield stress, namely $\sigma_{x\,max} = \sigma_Y$ for σ_{xav} or $\sigma_{y\,max} = \sigma_Y$ for σ_{yav}.

This assumption is relevant when the unloaded edges move freely in plane as that shown in Figure 18.40(b).

Another approximate method is to use the *plate effective width concept,* which provides the plate ultimate strength components under uniaxial compressive stresses (σ_{xu} and σ_{yu}), as follow:

$$\frac{\sigma_{xu}}{\sigma_Y} = \frac{b_{eu}}{b} \text{ and } \frac{\sigma_{yu}}{\sigma_Y} = \frac{a_{eu}}{a} \quad [54]$$

where a_{eu} and b_{eu} are the plate effective *length* and *width* at the *ultimate limit state*, respectively.

While a number of the plate effective width expressions have been developed, a typical approach is exemplified by Faulkner, who suggests an empirical effective width (b_{eu}/b) formula for simply supported steel plates, as follows,

- for longitudinal axial compression (34),

$$\frac{b_{eu}}{b} = \begin{cases} 1 & \text{for } \beta < 1 \\ \frac{c_1}{\beta} - \frac{c_2}{\beta^2} & \text{for } \beta \geq 1 \end{cases} \quad [55a]$$

- for transverse axial compression (35),

$$\frac{a_{eu}}{a} = \frac{0.9}{\beta^2} + \frac{b}{a}\frac{1.9}{\beta}\left(1 - \frac{0.9}{\beta^2}\right) \quad [55b]$$

where:

$\beta = \frac{b}{t}\sqrt{\frac{\sigma_Y}{E}}$ is the plate slenderness

E = the Young's modulus

t = the plate thickness

c_1, c_2 = typically taken as $c_1 = 2$ and $c_2 = 1$

The plate ultimate strength components under uniaxial compressive loads are therefore predicted by substituting the plate effective width formulae (equation 55a) into equation 54.

More charts and formulations are available in many books, for example, Bleich (36), ECCS-56 (37), Hughes (3) and Lewis (2). In addition, the design strength of plate (unstiffened panels) is detailed in Chapter 19, Subsection 19.5.4.1, including an example of reliability-based design and alternative equations to equations 51 and 55.

18.6.3.3 Design criteria

When a single load component is involved, the buckling or ultimate strength must be greater than the corresponding applied stress component with an appropriate target partial safety factor. In a multiple load component case, the structural safety check is made with equation 48 against buckling and equation 50 against *ultimate limit state* being satisfied.

To ensure that the possible worst condition is met (buckling and yield) for the ship, several stress combination must be considered, as the maximum longitudinal and transverse compression do not occur simultaneously. For instance, DNV (4) recommends:

- maximum compression, σ_x, in a plate field and phase angle associated with σ_y, τ (buckling control),
- maximum compression, σ_y, in a plate field and phase angle associated with σ_x, τ (buckling control),
- absolute maximum shear stress, τ, in a plate field and phase angle associated with σ_x, σ_y (buckling control), and
- maximum equivalent von Mises stress, σ_e, at given positions (yield control).

In order to get σ_x and σ_y, the following stress components may normally be considered for the buckling control:

σ_1 = stress from primary response, and
σ_2 = stress from secondary response (that is, double bottom bending).

As the lateral bending effects should be normally included in the buckling strength formulation, stresses from local bending of stiffeners (secondary response), σ_2^*, and local bending of plate (tertiary response), σ_3, must therefore not to be included in the buckling control. If FE-analysis is performed the local plate bending stress, σ_3, can easily be excluded using membrane stresses.

18.6.4 Buckling and Ultimate Strength of Stiffened Panels

For the structural capacity analysis of stiffened panels, it is presumed that the main support members including longitudinal girders, transverse webs and deep beams are designed with proper proportions and stiffening systems so that their instability is prevented prior to the failure of the stiffened panels they support.

In many ship stiffened panels, the stiffeners are usually attached in one direction alone, but for generality, the design criteria often consider that the panel can have stiffeners in one direction and webs or girders in the other, this arrangement corresponds to a typical ship stiffened panels (Figure 18.43a). The stiffeners and webs/girders are attached to only one side of the panel.

The number of load components acting on stiffened steel panels are generally of four types, namely biaxial loads, that is compression or tension, edge shear, biaxial in-plane bending and lateral pressure, as shown in Figure 18.43. When the panel size is relatively small compared to the entire structure, the influence of in-plane bending effects may be negligible.

However, for a large stiffened panel such as that in side shell of ships, the effect of in-plane bending may not be negligible, since the panel may collapse by failure of stiffeners which are loaded by largest added portion of axial compression due to in-plane bending moments.

When the stiffeners are relatively small so that they buckle together with the plating, the stiffened panel typically behaves as an orthotropic plate. In this case, the average values of the applied axial stresses may be used by neglecting the influence of in-plane bending. When the stiffeners are relatively stiff so that the plating between stiffeners buckles before failure of the stiffeners, the ultimate strength is eventually reached by failure of the most highly stressed stiffeners. In this case, the largest values of the axial compressive or tensile stresses applied at the location of the stiffeners are used for the failure analysis of the stiffeners. In stiffened panels of ship structures, material properties of the stiffeners including the yield stress are in some cases different from that of the plate. It is therefore necessary to take into account this effect in the structural capacity formulations, at least approximately.

For analysis of the ultimate strength capacity of stiffened panels which are supported by longitudinal girders, transverse webs and deep beams, it is often assumed that the panel edges are simply supported, with zero deflection and zero rotational restraints along four edges, with all edges kept straight.

This idealization may provide somewhat pessimistic, but adequate predictions of the ultimate strength of stiffened panels supported by heavy longitudinal girders, transverse webs and deep beams (or bulkheads).

Today, direct non-linear strength assessment methods using recognized programs is usual (38). The model should

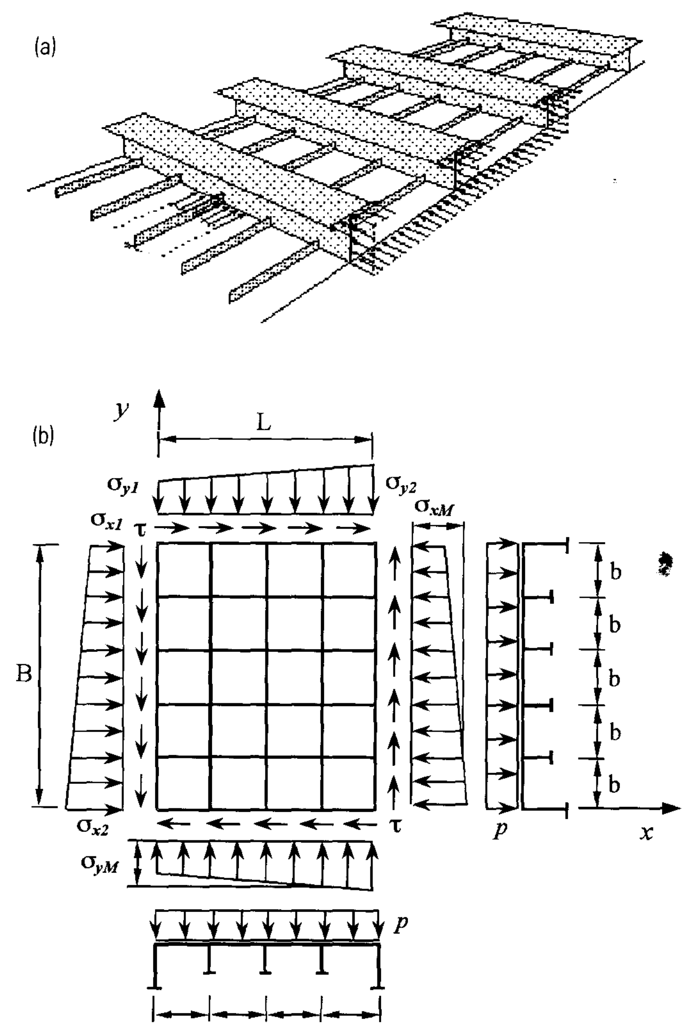

Figure 18.43 A Stiffened Steel Panel Under Biaxial Compression/Tension, Biaxial In-plane Bending, Edge Shear and Lateral Pressure Loads. (a) Stiffened Panel—Longitudinals and Frames (4), and (b) A Generic Stiffened Panel (38).

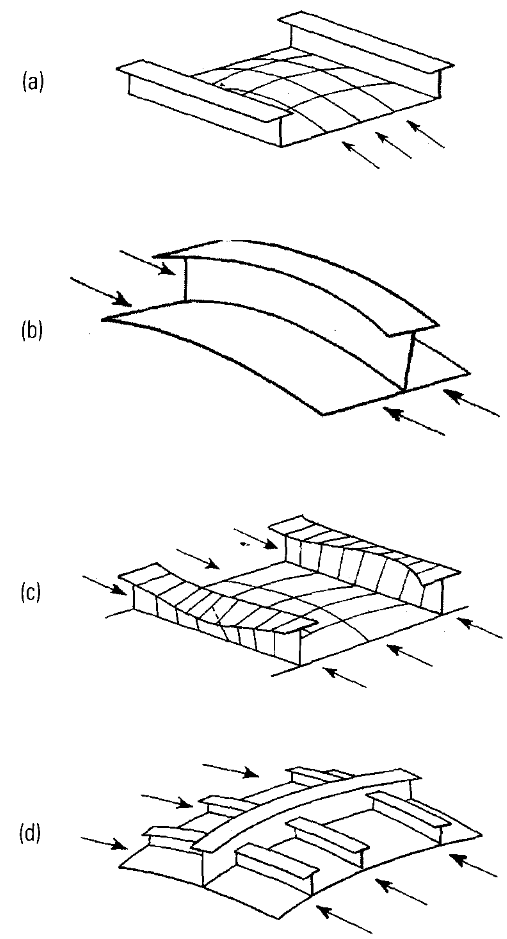

Figure 18.44 Modes of Failures by Buckling of a Stiffened Panel (2).
(a) Elastic buckling of plating between stiffeners (serviceability limit state).
(b) Flexural buckling of stiffeners including plating (plate-stiffener combination, mode III).
(c) Lateral-torsional buckling of stiffeners (tripping—mode V).
(d) Overall stiffened panel buckling (grillage or gross panel buckling—mode I).

be capable of capturing all relevant buckling modes and detrimental interactions between them. The fabrication related initial imperfections in the form of initial deflections (plates, stiffeners) and residual stresses can in some cases significantly affect (usually reduce) the ultimate strength of the panel so that they should be taken into account in the strength computations as parameters of influence.

18.6.4.1 Direct analysis

The primary modes for the ultimate limit state of a stiffened panel subject to predominantly axial compressive loads may be categorized as follows (Figure 18.44):

- Mode I: Overall collapse after overall buckling,
- Mode II: Plate induced failure-yielding of the plate-stiffener combination at panel edges,
- Mode III: Plate induced failure-flexural buckling followed by yielding of the plate-stiffener combination at mid-span,
- Mode IV: Stiffener induced failure-local buckling of stiffener web,
- Mode V: Stiffener induced failure-tripping of stiffener, and
- Mode VI: Gross yielding.

Calculation of the ultimate strength of the stiffened panel under combined loads taking into account all of the possible failure modes noted above is not straightforward, because of the interplay of the various factors previously noted such as geometric and material properties, loading, fabrication related initial imperfections (initial deflection and welding induced residual stresses) and boundary conditions. As an approximation, the collapse of stiffened panels is then usually postulated to occur at the lowest value among the various ultimate loads calculated for each of the alfve collapse patterns.

This leads to the easier alternative wherein one calculates the ultimate strengths for all collapse modes mentioned above separately and then compares them to find the minimum value which is then taken to correspond to the real panel ultimate strength. The failure mode of stiffened panels is a broad topic that cannot be covered totally within this chapter. Many simplified design methods have of course been previously developed to estimate the panel ultimate strength, considering one or more of the failure modes among those mentioned above. Some of those methods have been reviewed by the ISSC'2000 (39). On the other hand, a few authors provide a complete set of formulations that cover all the feasible failure modes noted previously, namely, Dowling et al (40), Hughes (3), Mansour et al (41,42), and more recently Paik (38).

Assessment of different formulations by comparison with experimental and/or FE analysis are available (43-45).

An example of reliability-based assessment of the.stiffened panel strength is presented in Chapter 19. Formulations of Herzog, Hughes and Adamchack are also discussed.

18.6.4.2 Simplified models

Existing simplified methods for predicting the ultimate strength of stiffened panels typically use one or more of the following approaches:

- orthotropic plate approach,
- plate-stiffener combination approach (or beam-column approach), and
- grillage approach.

These approaches are similar to those presented in Subsection 18.4.4.1 for linear analysis. All have the same background but, here, the buckling and the ultimate strength is considered.

In the *orthotropic plate approach,* the stiffened panel is idealized as an equivalent orthotropic plate by *smearing* the stiffeners into the plating. The orthotropic plate theory will then be useful for computation of the panel ultimate strength for the overall grillage collapse mode (Mode I, Figure 18.44d), (31,46,48).

The *plate-stiffener combination approach* (also called *beam-column* approach) models the stiffened panel behavior by that of a single *"beam"* consisting of a stiffener together with the attached plating, as representative of the stiffened panel (Figure 18.38, level 3b). The beam is considered to be subjected to axial and lateral line loads. The torsional rigidity of the stiffened panel, the Poisson ratio effect and the effect of the intersecting beams are all neglected. The *beam-column* approach is useful for the computation of the panel ultimate strength based on Mode III, which is usually an important failure mode that must be considered in design. The degree of accuracy of the *beam-column* idealization may become an important consideration when the plate stiffness is relatively large compared to the rigidity of stiffeners and/or under significant biaxial loading.

Stiffened panels are asymmetric in geometry about the plate-plane. This necessitates strength control for both plate induced failure and stiffener-induced failure.

Plate inducedfailure: Deflection away from the plate associated with yielding in compression at the connection between plate and stiffener. The characteristic buckling strength for the plate is to be used.

Stiffener inducedfailure: Deflection towards the plate associated with yielding in compression in top of the stiffener or torsional buckling of the stiffener.

Various column strength formulations have been used as the basis of the *beam-column* approach, three of the more common types being the following:

- Johnson-Ostenfeld (or Bleich-Ostenfeld) formulation,
- Perry-Robertson formulation, and
- empirical formulations obtained by curve fitting experimental or numerical data.

A stocky panel that has a high elastic buckling strength will not buckle in the elastic regime and will reach the *ultimate limit state* with a certain degree of plasticity. In most design rules of classification societies, the so-called Johnson-Ostenfeld formulation is used to account for this behavior (equation 47). On the other hand, in the so-called Perry-Robertson formulation, the strength expression assumes that the stiffener with associated plating will collapse as a beam-column when the maximum compressive stress in the extreme fiber reaches the yield strength of the material.

In empirical approaches, the ultimate strength formulations are developed by curve fitting based on mechanical collapse test results or numerical solutions. Even if limited to a range of applicability (load types, slenderness ranges, assumed level of initial imperfections, etc.) they are very useful for preliminary design stage, uncertainty assessment and as constraint in optimization package. While a vast number of empirical formulations (sometimes called column curves) for ultimate strength of simple beams in steel framed structures have been developed, relevant empirical formulae for plate-stiffener combination models are also available. As an example of the latter type, Paik and Thayamballi (49) developed an empirical formula for predicting the ultimate strength of a plate-stiffener combination under axial compression in terms of both column and plate slenderness ratios, based on existing mechanical collapse test data for the ultimate strength of stiffened panels under axial compression and with initial imperfections (initial deflections and residual stresses) at an *average* level. Since the ultimate strength of columns (σ_u) must be less than the elastic column buckling strength (σ_E), the *Paik-Thayamballi empirical formula* for a plate-stiffener combination is given by:

$$\frac{\sigma_u}{\sigma_Y} = \frac{1}{\sqrt{0.995 + 0.936\lambda^2 + 0.17\beta^2 + 0.188\lambda^2\beta^2 - 0.067\lambda^4}} \quad [56]$$

and

$$\frac{\sigma_u}{\sigma_Y} \leq \frac{1}{\lambda^2} = \frac{\sigma_E}{\sigma_Y}$$

with

$$\beta = \frac{b}{t}\sqrt{\frac{\sigma_Y}{E}}$$

and

$$\lambda = \frac{a}{\pi r}\sqrt{\frac{\sigma_Y}{E}} = \sqrt{\frac{\sigma_Y}{\sigma_E}}$$

where

r = radius of gyration
  $= \sqrt{I / A}$, (m)
I = inertia, (m^4)
A = cross section of the plate-stiffener combination with full attached plating, (m^2)
t = plate thickness, (m)
a = span of the stiffeners, (m)
b = spacing between 2 stiffeners, (m)

Note that A, I, r, ... refer to the full section of the plate-stiffener combination, that is, without considering an effective plating.

Figure 18.45 compares the Johnson-Ostenfeld formula (equation 47), the Perry-Robertson formula and the Paik-Thayamballi empirical formula (equation 56) for on the column ultimate strength for a plate-stiffener combination varying the column slenderness ratios, with selected initial eccentricity and plate slenderness ratios. In usage of the Perry-Roberson formula, the lower strength as obtained from either plate induced failure or stiffener-induced failure is adopted herein. Interaction between *bending axial*

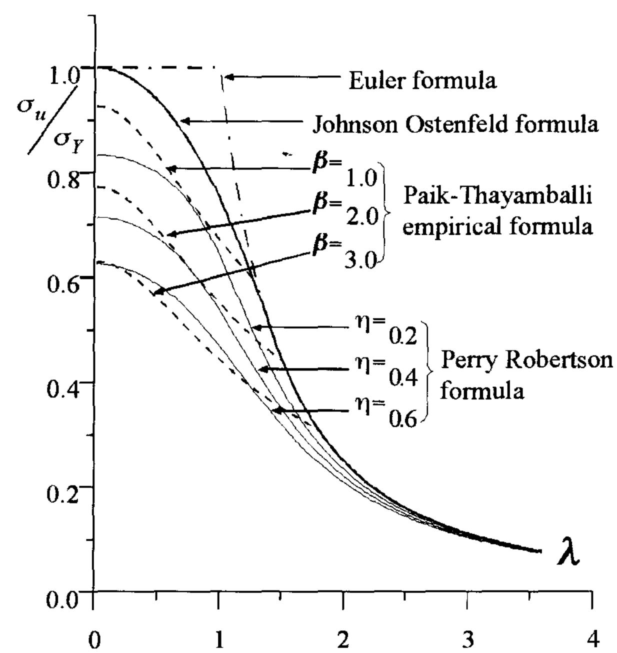

Figure 18.45 A Comparison of the Ultimate Strength Formulations for Plate-stiffener Combinations under Axial Compression (η relates to the initial deflection)

compression and *lateral pressure* can, within the same failure mode (Flexural Buckling-Mode III), leads to three-failure scenario: plate induced failure, stiffener induced failure or a combined failure of stiffener and plating (see Chapter 19 - Figure 19.11).

18.6.4.3 Design criteria

The ultimate strength based design criteria of stiffened panels can also be defined by equation 50, but using the corresponding stiffened panel ultimate strength and stress parameters. Either all of the six design criteria, that is, against individual collapse modes I to VI noted above, or a single design criterion in terms of the real (minimum) ultimate strength components must be satisfied. For stiffened panels following Mode I behavior, the safety check is similar to a plate, using average applied stress components. The applied axial stress components for safety evaluation of the stiffened panel following Modes II-VI behavior will use the maximum axial stresses at the most highly stressed stiffeners.

18.6.5 Ultimate Bending Moment of Hull Girder

Ultimate hull girder strength relates to the maximum load that the hull girder can support before collapse. These loads induce vertical and horizontal bending moment, torsional moment, vertical and horizontal shear forces and axial force. For usual seagoing vessels axial force can be neglected. As the maximun shear forces and maximum bending moment do not occur at the same place, ultimate hull girder strength should be evaluated at different locations and for a range of bending moments and shear forces.

The ultimate bending moment (M,,) refers to a combined vertical and horizontal bending moments (My, M_h); the transverse shear forces (Vy'Vh) not being considered. Then, the ultimate bending moment only corresponds to tne of the feasible loading cases that induce hull girder collapse. Today, Mu is considered as being a relevant design case.

Two major references related to the ultimate strength of hull girder are, respectively, for extreme load and ultimate strength, Jensen et al (24) and Yao et al (50). Both present comprehensive works performed by the Special Task Committees of ISSC 2000. Yao (51) contains an historical review and a state of art on this matter.

Computation of M_u depends closely on the ultimate strength of the structure's constituent panels, and particularly on the ultimate strength in compressed panels or components. Figure 18.46 shows that in *sagging*, the deck is compressed (σ_{deck}) and reaches the ultimate limit state when $\sigma_{deck} = \sigma_u$. On the other hand, the bottom is in tensile and reaches its ultimate limit state after complete yielding, $\sigma_{bottom} = \sigma_0$ (σ_0 being the yield stress).

Basically, there exist two main approaches to evaluate the hull girder ultimate strength of a ship's hull under longitudinal bending moments. One, *the approximate analysis*, is to calculate the ultimate bending moment directly (M_u, point C on Figure 18.46), and the other is to perform *progressive collapse analysis* on a hull girder and obtain, both, M_u and the curves M-ϕ.

The first approach, *approximate analysis*, requires an assumption on the longitudinal stress distribution. Figure 18.47 shows several distributions corresponding to different methods. On the other hand, the progressive collapse analysis does not need to know in advance this distribution.

Accordingly, to determine the global ultimate bending moment (M_u), one must know in advance

- the ultimate strength of each compressed panel (σ_u), and
- the average stress-average strain relationship (σ–ε), to perform a progressive collapse analysis.

For an approximate assessment, such as the Caldwell method, only the ultimate strength of each compressed panel (σ_u) is required.

18.6.5.1 Direct analysis

The direct analysis corresponds to the *Progressive collapse analysis*. The methods include the typical numerical analy-

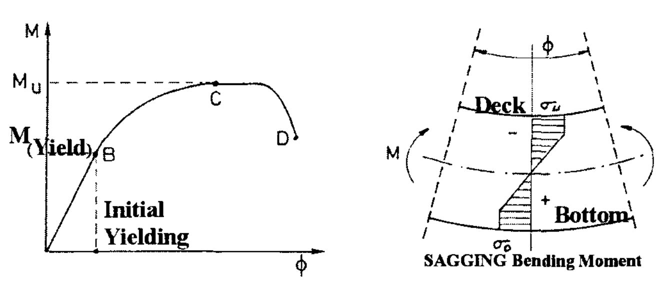

Figure 18.46 The Moment-Curvature Curve (M-Φ)

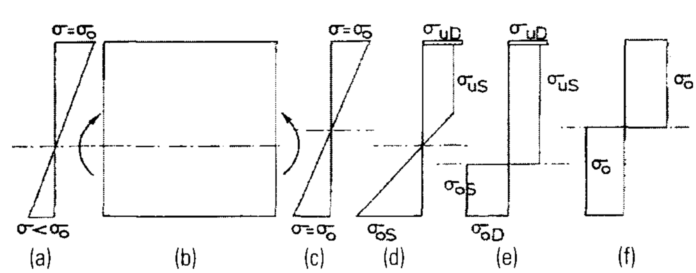

Figure 18.47 Typical Stress Distributions Used by Approximate Methods. (a) First Yield. (b) Sagging Bending Moment (c) Evans (d) Paik—Mansour (e) Caldwell Modified (f) Plastic Bending Moment.

sis such as Finite Element Method *(FEM)* and the Idealized structural Element method *(ISUM)* and *Smith's method,* which is a simplified procedure to perform progressive collapse analysis.

FEM: is the most rational way to evaluate the ultimate hull girder strength through a progressive collapse analysis on a ship's hull girder. Both material and geometrical nonlinearities can be considered.

A 3D analysis of a hold or a ship's section is fundamentally possible but very difficult to perform. This is because a ship's hull is too large and complicated for such kind of analysis. Nevertheless, since 1983 results ofFEM analyses have been reported (52). Today, with the development of computers, it is feasible to perform progressive collapse analysis on a hull girder subjected to longitudinal bending with fine mesh using ordinary elements. For instance, the investigation committee on the causes of the Nakhodka casualty performed elastoplastic large deflection analysis with nearly 200 000 elements (53).

However, the modeling and analysis of a complete hull girder using FEM is an enormous task. For this reason the analysis is more conveniently performed on a section ofthe hull that sufficiently extends enough in the longitudinal direction to model the characteristic behavior. Thus, a typical analysis may concern one frame spacing in a whole compartment (cargo tank). These analyses have to be supplemented by information on the bending and shear loads that act at the fore and aft transverse loaded sections. Such Finite Element Analysis (FEA) has shown that accuracy is limited because of the boundary conditions along the transverse sections where the loading is applied, the position of the neutral axis along the length of the analyzed section and the difficulty to model the residual stresses.

Idealized Structural Unit Method (ISUM): presefed in Subsection 18.7.3.1, can also be used to perform progressive collapse analysis. It allows calculating the ultimate bending moment through a 3D progressive collapse analysis of an entire cargo hold. For that purpose, new elements to simulate the actual collapse of deck and bottom plating are actually underdevelopment.

Smith's Method (Figure 18.48): A convenient alternative to FEM is the Smith's progressive collapse analysis (54), which consists of the following three steps (55).

Step I: Modeling (mesh modeling of the cross-section into elements),

Step 2: Derivation of *average stress-average strain* relationship of each element (cr-E *curve),* Figure 18.49a.

Step 3: To perform progressive collapse analysis, Figure 18.49b.

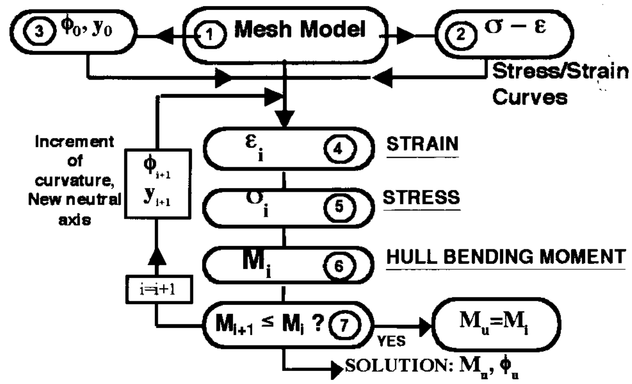

Figure 18.48 The Smith's Progressive Collapse Method

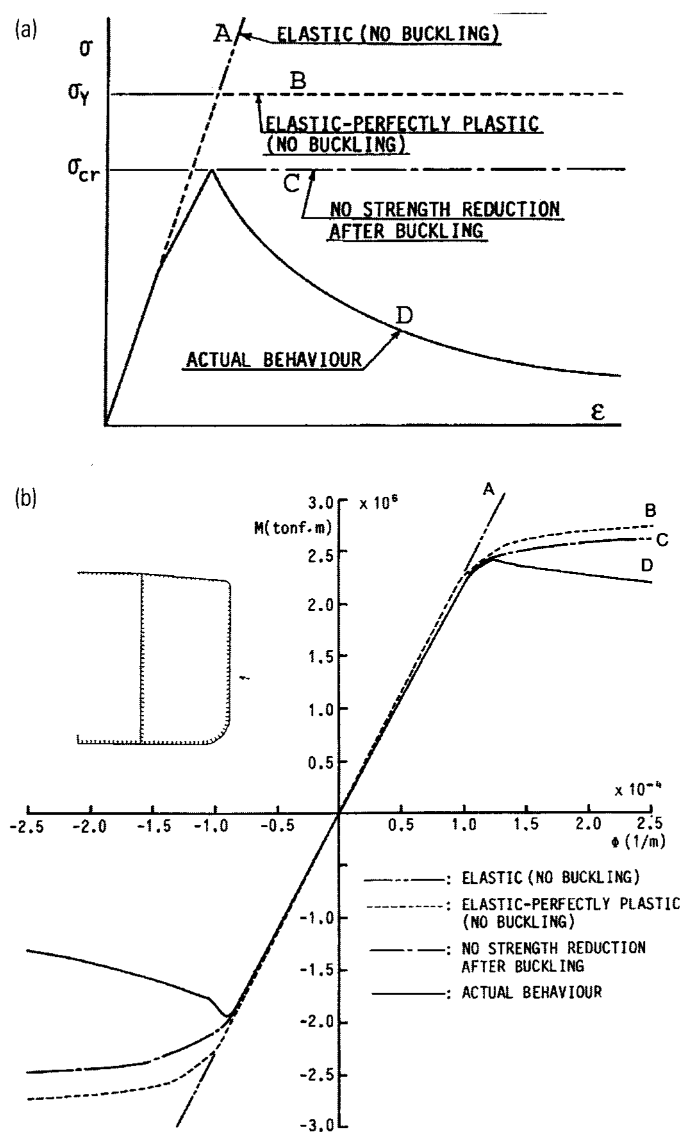

Figure 18.49 Influence of Element Average Stress-Average Strain Curves (σ–ε) on Progressive Collapse Behavior. (a) Average stress-average strain relationships of element, and (b) moment-curvature relationship of cross-section.

In Step 1, the cross-section of a hull girder is divided into elements composed of a longitudinal stiffener and attached plating. In Step 2, the *average stress-average strain* relationship (σ–ε) of this stiffener element is derived under the axial load considering the influences of buckling and yielding. Step 3 can be explained as follows:

- axial rigidities of individual elements are calculated using the *average stress-average strain* relationships (σ–ε),
- flexural rigidity of the cross-section is evaluated using the axial rigidities of elements,
- vertical and horizontal curvatures of the hull girder are applied incrementally with the assumption that the plane cross-section remains plane and that the bending occurs about the instantaneous neutral axis of the cross-section,
- the corresponding incremental bending moments are evaluated and so the strain and stress increments in individual elements, and
- incremental curvatures and bending moments of the cross-section as well as incremental strains and stresses of elements are summed up to provide their cumulative values.

Figure 18.48 shows that the σ–ε curves are used to estimate the bending moment carried by the complete transverse section (M_i). The contribution of each element (dM) depends on its location in the section, and specifically on its distance from the current position of the neutral axis (Y_i). The contribution will then also depend on the strain that is applied to it, since $\varepsilon = -y\ \phi$, where ϕ is the hull curvature and y is the distance from the neutral axis (simple beam assumption). The *average stress-average strain* curve (σ-ε) will then provide an estimate of the longitudinal stress (σ_i) acting on the section. Individual moments about the neutral axis are then summed to give the total bending moment for a particular curvature ϕ_i.

The accuracy of the calculated ultimate bending moment depends on the accuracy of the *average stress-average strain* relationships of individual elements. Main difficulties concern the modeling of initial imperfections (deflection and welding residual stress) and the boundary conditions (multi-span model, interaction between adjacent elements, etc.).

Many formulations and methods to calculate these *average stress-average strain* relationships are available: Adamchack (56), Beghin et al (57), Dow et al (58), Gordo and Guedes Soares (59,60) and, Yao and Nikolov (61,62). The FEM can even be used to get these curves (Smith 54).

For most of the methods, typical element types are: plate element, beam-column element (stiffener and attached plate) and hard corner.

An interesting well-studied ship that reached its ultimate bending moment is the *Energy Concentration* (63). It frequently is used as a reference case (benchmark) by authors to validate methods.

Figure 18.49 shows typical *average stress-average strain* relationships, and the associated bending moment-curvature relationships (M-ϕ). Four typical σ–ε curves are considered, which are:

Case A: Linear relationship (elastic). The M-ϕ relationship is free from the influences of yielding and buckling, and is linear.

Case B: Bi-linear relationship (elastic-perfectly plastic, without buckling).

Case C: With buckling but without strength reduction beyond the ultimate strength.

Case D: With buckling and a strength reduction beyond the ultimate strength (actual behavior).

In Case B, where yielding takes place but no buckling, the deck initially undergoes yielding and then the bottom. With the increase in curvature, yielded regions spread in the side shell plating and the longitudinal bulkheads towards the plastic neutral axis.

In this case, the maximum bending moment is the fully plastic bending moment (Mp) of the cross-section and its absolute value is the same both in the sagging and the hogging conditions.

For Cases C and D, the element strength is limited by plate buckling, stiffener flexural buckling, tripping, etc. For Case C, it is assumed that the structural components can continue to carry load after attaining their ultimate strength. The collapse behavior (M-ϕ curve) is similar to that of Case B, but the ultimate strength is different in the sagging and the hogging conditions, since the buckling collapse strength is different in the deck and the bottom.

Case D is the actual case; the capacity of each structural member decreases beyond its ultimate strength. In this case, the bending moment shows a peak value for a certain value of the curvature. This peak value is defined as the ultimate longitudinal bending moment of the hull girder (M_u).

Shortcomings and limitations of the Smith's method relates to the fact that a typical analysis concerns one frame spacing of a whole cargo hold and not a complete 3D hold.

As simple linear beam theory is used, deviations such as shear lag, warping and racking are thus ignored. This method may be a little un-conservative if the structure is predominantly subjected to lateral pressure loads as well as axial compression, and if it is not realized that the transverse frames can deflect/fail and significantly affect the stiffened plate structure and hull girder bending capacity.

18.6.5.2 Simplified models

Caldwell (64) was the first who tried to theoretically evaluate the ultimate hull girder strength of a ship subjected to longitudinal bending. He introduced a so-called *Plastic Design* considering the influence of buckling and yielding of structural members composing a ship's hull (Figure 18.47).

He idealised a stiffened cross-section of a ship's hull to an unstiffened cross-section with equivalent thickness. If buckling takes place at the compression side of bending, compressive stress cannot reach the yield stress, and the fully plastic bending moment (Mp) cannot be attained. Caldwell introduced a stress reduction factor in the compression side of bending, and the bending moment produced by the reduced stress was considered as the ultimate hull girder strength.

Several authors have proposed improvements for the Caldwell formulation (65). Each of them is characterized by an assumed stress distribution (Figure 18.47). Such methods aim at providing an estimate of the ultimate bending moment without attempting to provide an insight into the behaviour before, and more importantly, after, collapse of the section. The tracing out of a progressive collapse curve is replaced by the calculation of the ultimate bending moment for a particular distribution of stresses. The quality of the direct approximate method is directly dependent on the quality of the stress distribution at collapse. It is assumed that at collapse the stresses acting on the members that are in tension are equal to yield throughout whereas the stresses in the members that are in compression are equal to the individual inelastic buckling stresses. On this basis, the plastic neutral axis is estimated using considerations of longitudinal equilibrium. The ultimate bending moment is then the sum of individual moments of all elements about the plastic neutral axis.

In Caldwell's Method, and Caldwell Modified Meth\\ds, reduction in the capacity of structural members beyond tfieir ultimate strength is not explicitly taken into account. This may cause the overestimation of the ultimate strength in general (Case C, Figure 18.49).

Empirical Formulations: In contrast to all the previous rational methods, there are some empirical formulations usually calibrated for a type of specific vessels (66,67). Yao et al (50), found that *initial yielding* strength of the deck can provide in general a little higher but reasonably accurate estimate of the ultimate sagging bending moment. On the other hand, the *initial buckling strength* of the bottom plate gives a little lower but accurate estimate of the ultimate hogging bending moment. These in effect can provide a first estimate of the ultimate hull girder moment.

Interactions: In order to raise the problem of combined loads (vertical and horizontal bending moments and shear forces), several authors have proposed empirical interaction equations to predict the ultimate strength. Each load component is supposed to act separately. These methods were reviewed by ISSC (68) and are often formulated .as equation 57.

$$\left(\frac{M_v}{M_{vu}}\right)^a + \alpha\left(\frac{M_h}{M_{hu}}\right)^b = 1 \qquad [57]$$

where:

M_v and M_h = vertical and horizontal bending moments
M_{vu} and M_{hu} = ultimate vertical and horizontal bending moments
a, b and α = empirical constants

For instance, Mansour et al (47) proposes a=1, b=2 and α= 0.8 based on analysis on one container, one tanker and 2 cruisers, and Gordo and Soares (60) 1.5<a=b<1.66 and α= 1.0 for tankers. Hu et al (69) has proposed similar formulations for bulk carriers. Paik et al (70) proposes an empirical formulation that includes the shear forces in addition to the bending moments.

18.6.5.3 Design criteria

For design purpose, the value of the ultimate longitudinal bending moment (capability) has to be compared with the extreme bending moment (load) that may act on a ship's hull girder. To estimate the extreme bending moment, the most severe loading condition has to be selected to provide the maximum still water bending moment. Regarding the wave bending moment, the lACS unified requirement is a major reference (71,72), but more precise discussions can be found in the ISSC 2000 report (24).

To evaluate the ultimate longitudinal strength, various methods can be applied tanging from simple to complicated methods. In 2000, many ofthe available methods were examined and assessed by an ISSC'2000 Committee (50). The grading of each method with respect to each *capability* is quantitatively performed by scoring 1 through 5. The committee concluded that the appropriate methods should be selected according to the designer's needs and the design stage. That is, at early design stage, a simple method based on an *Assumed Stress Distribution* can be used to obtain a rough estimate of the ultimate bending moment. At later stages, a more accurate method such as *Progressive Collapse Analysis with calculated* Q"-E *curves (Smith's Method)* or *ISUM* has to be applied.

Main sensitive *model capability* with regards to the assessment of ultimate strength can be ranked in 3 classes, respectively, *high* (H), *medium* (M) and *low* (L) consequence of omitting capability (Table 18.IV).

Based on the different sources of uncertainties (model-

TABLE 18.IV Sensitivity Factors for Ultimate Strength Assessment of Hull Girder.

Model Capability	*Impact*
Plate buckling	H
Stiffened plate buckling	H
Post buckling behavior	H
Plate welding residual stress	H
M-ϕ curve (post collapse prediction)	H
Plate initial deflection	M
Stiffener initial deflection	M
Stiffener welding residual stress	M
Multi-span model (instead of single span) (see Figure 19.12 – Chapter 19)	H

ing, σ–ε curves, curvature incrementation), the global uncertainty on the ultimate bending moment is usually large (55). A bias of 10 to 15% must be considered as acceptable.

For intact hull the design criteria for M_u, defined by classification societies, is given by:

$$M_S + s_1 M_w \leq s_2 M_U \qquad [58]$$

where:

s_1 = the partial safety factor for load (typically 1.10)
s_2 = the material partial safety factor (typically 0.85)
M_S = still water moment
M_w = design wave moment (20 year return period)

18.6.6 Fatigue and Fracture

18.6.6.1 General

Design criteria stated expressly in terms of fatigue damage resistance were in the past seldom employed in ship structural design although cumulative fatigue criteria have been used in offshore structure design. It was assumed that fatigue resistance is implicitly included in the conventional safety factors or acceptable stress margins based on past experience.

Today, fatigue considerations become more and more important in the design of details such as hatch comers, reinforcements for openings in structural members and so on. Since the ship-loading environment consists in large part of alternating loads, ship structures are highly sensitive to fatigue failures. Since 1990, fatigue is maybe the most sensitive point at the detailed design stage. Tools are available but they are time consuming and there is large uncertainty of using simplified methods ..

With the introduction of higher tensile steels in hull structures, at first in deck and bottom to increase hull girder strength, and later in local structures, the fatigue problem became more imminent. The fatigue strength does not increase according to the yield strength of the steel. In fact, fatigue is found to be independent of the yield strength. The higher stress levels in modem hull structures using higher tensile steel have therefore led to a growing number of fatigue crack problems.

To ensure that the structure will fulfill its intended function, fatigue assessment should be carried out for each individual type of structural detail that is subjected to extensive dynamic loading. It should be noted that every welded joint and attachment or other form of stress concentration is potentially a source of fatigue cracking and should be individually considered.

This section gives an overview of feasible analysis to be performed. A more complete description of the different fatigue procedures, S-N curves, stress concentration factors, and so on, are given in: Almar-Naess (73), DNV (4), Fricke et al (74), Maddox (75), Niemi (76), NRC (77) and Petershagen et al (78). Reliability-based fatigue procedure is presented by Ayyub and Assakkaf in Chapter 19. These authors also have contributed to this section.

18.6.6.2. Basic fatigue theories

Fatigue analyses can be performed based on:

- simplified analytical expressions,
- more refined analysis where loadings/load effects are calculated by numerical analysis, and
- a combination of simplified and refined techniques.'

There are generally two major technical approaches for fatigue life assessment of welded joints the *Fracture Mechanics Approach* and the *Characteristic S-N Curves Approach.*

The *Fracture Mechanics Approach* is based on crack growth data assuming that the crack initiation already exists. The initiation phase is not modeled as it is assumed that the lifetime can be predicted only using fracture mechanics method of the growing cracks (after initiation). The fracture mechanics approach is obviously more detailed than the *S-N* curves approach. It involves examining crack growth and determining the number of load cycles that are needed for small initial defects to grow into cracks large enough to cause fractures. The growth rate is proportional to the stress range, S (or ~cr) that is expressed in terms of a stress intensity factor, *K,* which accounts for the magnitude of the stress, current crack size, and weld and joint details. The basic equation that governs crack growth (79) is known as the *Paris Law* is:

$$\frac{da}{dN} = C.(\Delta K)^m \qquad [59]$$

where:

a = crack size,
N = number of fatigue cycles (fatigue life),
$\Delta K = S.Y(a).\sqrt{\pi a}$, range of stress intensity factor, ($K_{max} - K_{min}$)
C, m = crack propagation parameters,
S = constant amplitude stress range,
$= \Delta\sigma = \sigma_{max} - \sigma_{min}$
Y(a) = function of crack geometry.

Fatigue life prediction based on the fracture mechanics approach shall be computed according to the following equation:

$$N = \frac{1}{C.S^m}\int_{a_0}^{a}\frac{da}{Y^m} \qquad [60]$$

Equation 60 involves a variety of sources of uncertainty and practical difficulties to define, for instance, the a and a_0 crack size. The crack propagation parameter C in this equation is treated as random variable (80). However, in more sophisticated models, equation 60 is treated as a stochastic differential equation and C is allowed to vary during the crack growth process. State of art on the Fracture Mechanics Approach is available in Niemi (76) and Harris (81).

The *characteristic S-N curves approach* is based on fatigue test data *(S-N* curves-Figure 18.50) and on the assumption that fatigue damage accumulation is a linear phenomenon (Miner's rule). According to Miner (82) the total fatigue life under a variety of stress ranges's the weighted sum of the individual lives at constant stress range S as given by the S-N curves (Figure 18.50), with each being weighted according to fractional exposure to that level of stress range.

The S-N curve approach related mainly to the crack initiation and a maximum allowable crack size. After, cracks propagate based on the fracture mechanics concept as shown in Figure 18.51. The propagation is not explicitly considered by the S-N curve approach.

Fatigue life strength prediction based on both the S-N approach and Miner's cumulative damage shall be evaluated with equation 61 or, in logarithmic form, with equation 62 (Figure 18.50).

$$N = \frac{\Delta A}{k_S^m \, \bar{S}_e^m} \qquad [61]$$

$$\log N = \log(\Delta A) - m \log(\Delta\sigma) \qquad [62]$$

where:

Δ = fatigue damage ratio (≤ 1)
$\log(\Delta A)$ = intercept of the *S-N* curve of the *Log N* axis
$-1/m$ = slope of the *S-N* curve, ($\cong 3 \leq m \leq \cong 7$)
$\bar{S}_e$ = mean of the Miner's equivalent stress range S_e, defined at Table 18.V
k_S = fatigue stress uncertainty factor
$\Delta\sigma = k_S.\bar{S}_e$ (or the constant amplitude stress range for failure at N cycles)
N = fatigue life, or number of loading cycles expected during the life of a detail

The Miner's equivalent stress range, S_e, can be evaluated based on the models provided in Table 18.V (83). The most refined model would start with a scatter diagram of sea-states, information on ship's routes and operating char-

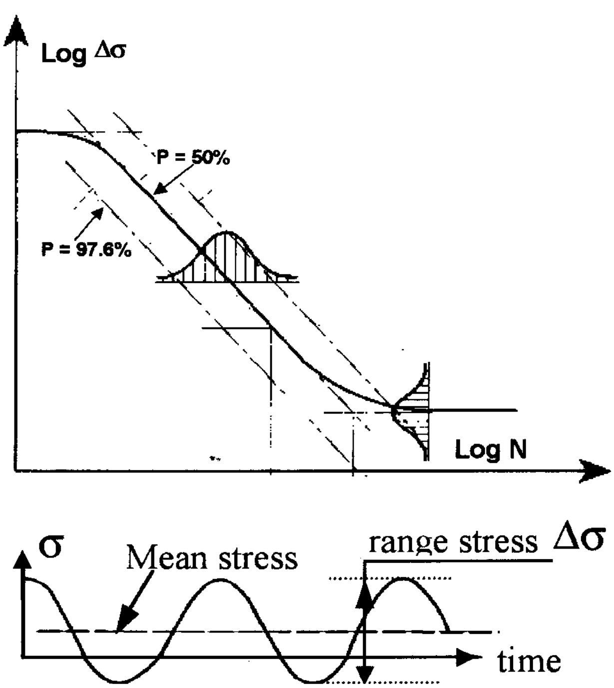

Figure 18.50 A Typical S-N Curve

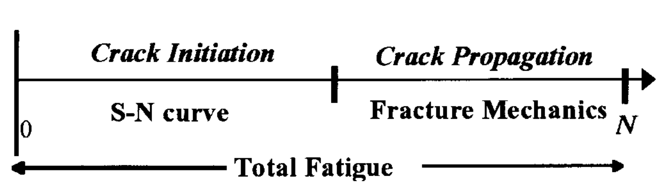

Figure 18.51 Comparison between the Characteristic S-N Curve and Fracture Mechanics Approach

acteristics, and use of a ship response computer program to provide a detailed history of stress ranges over the service life of the ship. For such model, the wave exceedance diagram (deterministic method) and the spectral method (probabilistic method) can be employed (Table l8.V).

S-N curves are obtained from fatigue tests and are available in different design codes for various structural details in bridges, ships, and offshore structures. The design S-N curves are based on the mean-minus-two-standard-deviation curves for relevant experimental data (Figure 18.50). They are thus associated with a 97.6% probability of survival. Some classification societies use 90%.

In practice, the actual probabilities of failure associated with fatigue design lives is usually higher due to uncertainties associated with the calculated stresses, the various S-N curve correction factors, and the critical value of the cumulative fatigue damage ratio, ~.

Cumulative damage: The damage may either be calculated on basis of the long-term stress range distribution using Weibull parameters (simplified method), or on summation of damage from each short-term distribution in the scatter diagram (probabilistic and deterministic methods, Table I8.V).

The stress range (S *or ~a):* The procedure for the fatigue analysis is based on the assumption that it is only necessary to consider the ranges of cyclic principal stresses in determining the fatigue endurance. However, some reduction in the fatigue damage accumulation can be credited when parts of the stress cycle range are in compression.

Fatigue areas: The potential for fatigue damage is dependent on weather conditions, ship type, corrosion level, location on ship, structural detail and weld geometry and workmanship. The potential danger of fatigue damage will also vary according to crack location and number of potential damage points. Fatigue strength assessmenishall normally be carried out for:

- longitudinal and transverse element in:
  - bottom/inner bottom (side),
  - longitudinal and transverse bulkheads.
- strength deck in the midship region and forebody, and
- other highly stressed structural details in the midship region and forebody, like panel knuckles.

Time at sea: Vessel response may differ significantly for different loading conditions. It is therefore of major importance to include response for actual loading conditions. Since fatigue is a result of numerous cyclic loads, only the most frequent loading conditions are included in the fatigue analysis. These will normally be ballast and full load condition. Under certain circumstances, other loading conditions may be used.

Environmental conditions: The long-term distribution of load responses for fatigue analyses may be estimated using the wave climate, represented by the distribution of Hs and Ts, representing the sea operation conditions. As guidance to the choice between these data sets, one should consider the average wave environment the vessel is expected to encounter during its design life. The world wide sailing routes will therefore normally apply. For shuttle tankers and vessels that will sail frequently on the North Atlantic, or in other harsh environments, the wave data given in accordance with this should be applied. For vessels that will sail in more smooth sailing routes, less harsh environmental data may be applied. This should be decided upon for each case.

Geometrical impeifections: The fatigue life of a welded joint is much dependent on the local stress concentrations factors arising from surface imperfections during the fabrication process, consisting of weld discontinuities and geometrical deviations. Surface weld discontinuities are weld toe undercuts, cracks, overlaps, incomplete penetration, etc. Geometrical imperfections are defined as misalignment, angular distortion, excessive weld reinforcement and otherwise poor weld shapes.

Effect of grinding of welds: For welded joints involving potential fatigue cracking from the weld toe an improvement in strength by a factor of at least 2 on fatigue life can be obtained by controlled local machining or grinding of the weldtoe. Note that grinding of welds should not be used as a "design tool", but rather as a mean to lower the fatigue damage when special circumstances have made it necessary. This should be used as a reserve if the stress in special areas turns out to be larger than estimated at an earlier stage of the design.

18.6.6.3 Stress concentration and hot spot stress

The stress level obtained from a structural analysis, such as FEA, will depend on the fineness of the model. The different analysis models described in Subsection 18.7.2 will therefore lead to different levels of result processing in order to complete the fatigue calculations.

In order to correctly determine the stresses to be used in fatigue analyses, it is important to note the definition of the different stress categories (Figure 18.52).

Nominal stresses are those, typically, derived from coarse mesh FE models. Stress concentrations resulting from the gross shape of the structure, for example, shear lag effects, have to be included in the nominal stresses derived from stress analysis.

Geometric stresses include nominal stresses and stresses due to structural discontinuities and presence of attachments, but excluding stresses due to presence of welds.

Stresses derived from fine mesh FE models are geometric stresses. Effects caused by fabrication imperfections as misalignment of structural parts, are normally not included in FEA, and must be separately accounted for, using, for instance (equation 65).

Hot spot stress is the greatest value of the extrapolation to the weld toe of the geometric stress distribution immediately outside the region affected by the geometry of the weld (Figure 18.52).

Notch stress is the total stress at the weld toe (hot spot location) and includes the geometric stress and the stress due to the presence of the weld. The notch stress may be calculated by multiplying the hot spot stress by a stress concentration factor, or more precisely the theoretical notch factor, K_2 (equation 65).

FE may be used to directly determine the notch stress. However, because of the small notch radius and the steep stress gradient at a weld, a very fine mesh is needed.

In practice, the stress concentration factors (K-factors) may be determined based on fine mesh FE analyses, or, alternatively, from the selection of factors for typical details.

The notch stress range governs the fatigue life of a detail. For components other than smooth specimens the notch stress is obtained by multiplication of the nominal stress by K-factors (equation 63). The K-factors in this 'document are thus defined as

$$K = \frac{\sigma_{notch}}{\sigma_{nominal}} \qquad [63]$$

The relation between *the notch stress range* to be used together with the S-N-curve and the nominal stress range is

$$S = \Delta\sigma = \Delta\sigma_{notch} = K.\Delta\sigma_{nominal} \qquad [64]$$

All stress risers have to be considered when evaluating

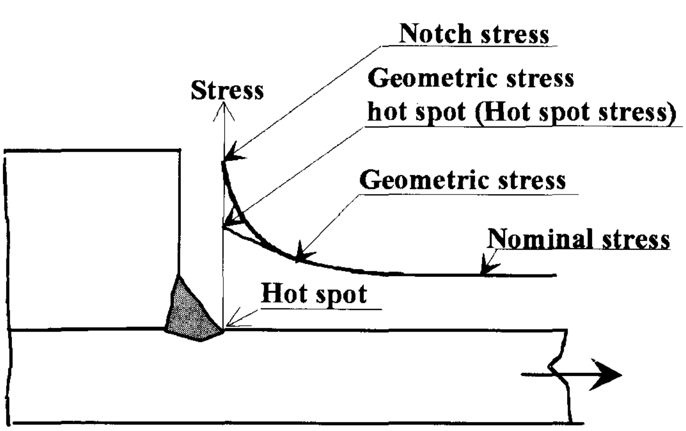

Figure 18.52 Definition of Stress Categories (4)

the notch stress. This can be done by multiplication of K-factors arising from different causes. The resulting K-factor to be used for calculation of notch stress is:

$$K = Kl \;.\; K2 \;.\; K3 \;.\; K4 \;.\; K5 \qquad [65]$$

where:

KJ = stress concentration factor due to the gross geometry of the detail considered

K_2 = stress concentration factor due to the weld geometry (notch factor); K_2 = 1.5 if not stated otherwise

K3 = additional stress concentration factor due to eccentricity tolerance

K4 = additionally stress concentration factor due to angular mismatch

Ks = additional stress concentration factor for un-symmetrical stiffeners on laterally loaded panels, applicable when the nominal stress is derived from simple beam analyses

Fatigue cracks are assumed to be independent of principal stress direction within 45° of the normal to the weld toe.

Hot spot stress extrapolation procedure: The hot spot stress extrapolation procedure (Figure 18.52) is only to be used for stresses that are derived from stress concentration models (fine mesh). Nominal stresses found from other models should be multiplied with appropriate stress concentration factors (equation 65). The stress extrapolation procedure is specific to each classification societies (74). Today, there is unfortunately no standard procedure.

18.6.6.4 Direct analysis

Several S-N fatigue approaches exists, they all have advantages and disadvantages. The different approaches are therefore suitable for-different areas. Load effects, accuracy of the analysis, computer demands, etc. should be evaluated before one of the approaches is chosen.

Full stochastic fatigue analysis: The full stochastic analysis, for example the *Spectral Model* of Table l8.V, is an analysis where all load effects from global and local loads, are included. This is ensured by use of *stress concentration models* and *direct load transfer* to the structural model. Hence, all stress components are combined using the correct phasing and without simplifications or omissions of any stress component.

This method usually will be the most exact for determination of fatigue damage and will normally be used together with fine meshed stress concentration models. The method may, however, not be suitable when non-linearities in the loading are of importance (side longitudinals). This is especially the case for areas where wave or tank pressures in the surface region are of major importance. This is due to

TABLE 18.V Commonly Used Expressions for Evaluating Miner's Equivalent Stress Range (S_e), (83)

1. Wave Exceedance Diagram (Deterministic Method)

$$S_e^m = \sum_i^{n_b} f_i S_i^m \rightarrow S_e = \sqrt[m]{\sum_i^{n_b} f_i S_i^m}$$

S_i = stress range

F_i = fraction of cycles in the *i*th stress block

n_b = number of stress block

2. Spectral Method (Probabilistic Method)

$$S_e^m = \lambda(m) \frac{\left(2\sqrt{2}\right)^m}{f_0} \Gamma\left(\frac{m}{2}+1\right) \sum_i \gamma_i f_i \sigma_i^m$$

$\lambda(m)$ = rainflow correction

$\Gamma(.)$ = gamma function

γ_i = fraction of time in *i*th sea-state

f_i = frequency of wave loading in *i*th sea-state

σ_i = RMS of stress process in *i*th sea-state

3. Weibull Model for Stress Ranges (Simplified Method)

$$S_e^m = S_d \left[\ln\left(N_d\right)\right]^{-\frac{m}{k}} \Gamma\left(\frac{m}{k}+1\right)$$

S_d = stress range that is exceeded on the average once out of N_d stress cycles

$\Gamma(.)$ = gamma function

k = Weibull shape parameter

N_d = total number of stress ranges in design life

the fact that all load effects result in one set of combined stresses, making it difficult to modify the stress caused by one of the load effects.

The approach is suitable for areas where the stress concentration factors are unknown (knuckles, bracket and flange terminations of main girder, stiffeners subjected to large relative deformations).

18.6.6.5 Simplified models

The stress component based stochastic fatigue analysis: The idea of the stress component based fatigue analysis is to change the *direct load transfer functions* calculated from the hydrodynamic load program into *stress transfer functions* by use ofload/stress ratios, Hi (equation 66). The load transfer functions, Hi' normally include the global hull girder bending sectional forces and moments, the pressures for all panels of the 3-D diffraction model, the internal tank pressures.

The stress transfer functions, Hi' are combined to a total stress transfer function, H", by a linear complex summation of the different transfer functions (4), as:

$$H_\sigma = \sum_i A_i H_i \qquad [66]$$

where:

Ai = stress per unit axial force defined as the local stress response in the considered detail due to a unit sectionalload for load component i.

H" = total transfer function for the combined local stress,

Hi = transfer function for the load component i, that is, axial force, bending moments, twisting and lateral load.

This approach enables the use of separate load factors on each load component and thus includes loads non-linearities. Few load cases have to be analyzed and it is possible to use simplified formulas for the area of interest but errors are easily made in the combination of stresses, manual definition of extra load cases may cause errors and simplifications are usually made in loading. Suitable areas are components where geometric stress concentration factors, KJ' are available (longitudinals, plating, cut-outs and standard hopper knuckles) and areas where side pressure is of importance.

The simplified design wave approach (Weibull Model, Table 18.V) is a simplification to the previous *component based stochastic fatigue analyses.* In this simplified approach, the extreme load response effect over a specified number of load cycles, for example, 10^4 cycles, is determined. The resulting stress range, ~cr, is then representative for the stress at a probability level of exceedance of 10^{-4} per cycle. The derived extreme stress response is combined with a calculated Weibull shape parameter, k, to define the long-term stress range distribution (Table I8.V). The Weibull shape parameter, k, for the stress response should be determined from the long-term distribution ofthe dominating load calculated in the hydrodynamic analysis.

This simplified approach only requires the consideration of one load case. It is easy and fast to perform but it can only be used if one load dominates the response and the results are very sensitive to selection of design wave. Suitable areas concern components where one load is dominating the response, that is, deck areas and other areas without local loading.

18.6.6.6 Design criteria

The standard fatigue design criterion is basically the expected lifetime before that significant damage appears (cracks). It usually is taken as being 20 years. Then, the designer's target is to design structural details for which the fatigue failure happens after, for instance, 20 years. If it happens before, the fixing cost is very high and induces owner losses. If the first failure only happens after 30 years or later, the structural detail scantlings were globally overestimated, the hull weight too high and, therefore, that the owner had lost payload during 20 years.

Partial safety factors, additional stress concentration factors and the stress extrapolation procedure are typically defined by the classifications societies.

18.6.7 Collision and Grounding

18.6.7.1 Present design approaches

The OPA 90 and equivalent IMO requirements must be satisfied in structural design of ships carrying dangerous or pollutant cargoes, for example, chemicals, bulk oil, liquefied gas. The primary requirements are to arrange a double bottom of a required minimum height, and double sides of a required minimum width. In this context, to reduce the outflow of pollutant cargoes in ship collision or grounding accident, OPA 90 and IMO both require that the minimum vertical height, h, of each double bottom ballast tank or void space is not to be less than 2.0 m or B/15 (B = ship's beam), whichever is the lesser, but in no case is the height to be less than 1.0 m. OPA and IMO also require that the minimum width, w, of each wing ballast tank or void space is not to be less than 0.5+DWT/20 000 (m) or w =2.0 (m), whichever is the lesser, where DWT is the deadweight of the ship in tonnes. In no case is w to be less than 1~ (m). More detailed information is available in Chapter 29'tm Oil Tanker.

18.6.7.2 Direct analysis

To reduce the probability of outflow of hazardous cargo in ship collisions and grounding, the kinetic energy loss during the accident should be entirely absorbed by damage of outer structures, that is, before the inner shell in contact with the cargo can rupture. Of crucial importance, then, is how to arrange or make the scantlings of strength members in the implicated ship structures such that the initial kinetic energy is effectively consumed and the structural performance against an accident will be maximized. For this purpose, the structural crashworthiness of ships in collisions and grounding must be analyzed using accurate and efficient procedures (84).

Figure 18.53 shows direct design procedures of ship structures against collision and grounding (85). For the *accidentallimit state* design, the integrity of a structure. can be checked in two steps. In the first step, the structuralperformance against design accident events will be assessed, while post-accident effects such as likely oil outflow are evaluated in the second step.

The primary concern of the *accidental limit state* design in such cases is to maintain the water tightness of ship compartments, the containment of dangerous or pollutant cargoes, and the integrity of critical spaces (reactor compartments of nuclear powered ships or tanks in LNG ships) at the greatest possible levels, and to minimize the release/outflow of cargo. To facilitate a rescue mission, it is also necessary keep the residual strength of damaged structures at a certain level, so that the ship can be towed to safe harbor or a repair yard as may be required.

18.6.7.3 Simplified models

Since the response of ships in collision or grounding accident includes relatively complicated behavior such as crushing, tearing and yielding, existing simplified methods are not always adequate. However, many simplified models useful for predicting accident induced structural damages and residual strength of damaged ship structures have been developed and continue to be successfully used. Simplified models for collision are rather different from those of grounding since both are different in the nature of the mechanics involved. As it is impossible to describe them in a limited space, valuable references are Ohtsubo et al (86), and Kaminski et al (39).

18.6.7.4 Design criteria

The structural design.criteria for ship collisions and grounding are based on limiting accidental consequences such as structural damage, fire and explosion, and environmental pollution, and to make sure that the main safety functions of ship structures are not impaired to a significant extent during any accidental event or within a certain time period thereafter.

Structural performance of a ship against collision or grounding can be measured by:

- energy absorption capability,
- maximum penetration in an accident,
- spillage amount of hazardous cargo, for example, crude oil, and
- hull girder ultimate strength of damaged ships (Section 18.6.5).

Design acceptance criteria may be based on the following parameters (87):

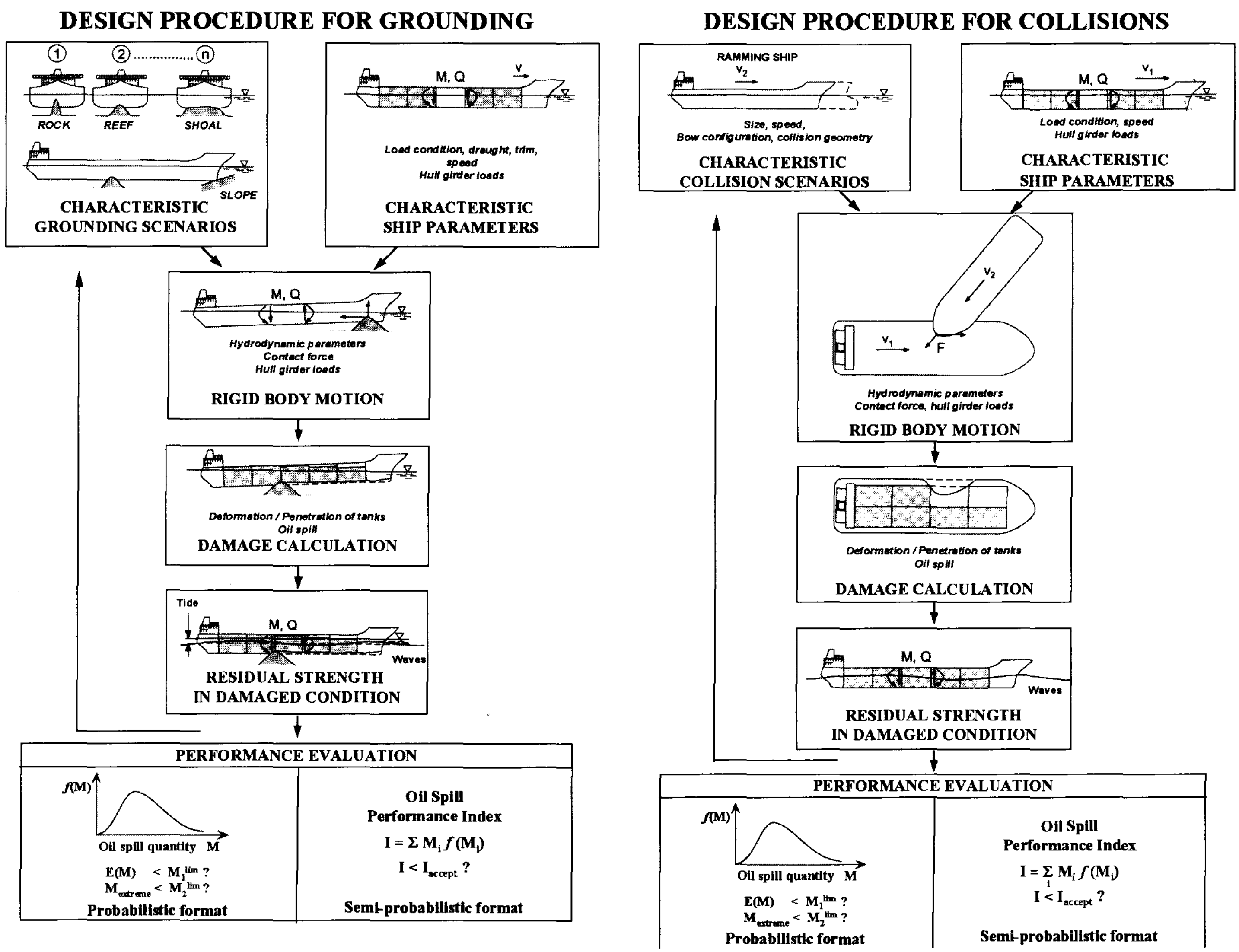

Figure 18.53 Structural Design Procedures of Ships for Collision and Grounding (85)

- minimum distance of cargo containment from the outer shell,
- ship speed above which a critical event (breaching of cargo containment) happens,
- allowable quantity of oil outflow, and
- minimum values of section modulus or ultimate hull girder strength.

And the design results must satisfy:

- cargo tanks/holds are not breached in an accident so that there will be no danger of pollution, or
- if the cargo tanks are breached, the oil outflow following an accident is limited, and/or
- the ship has adequate residual hull girder strength so that it will survive an accident and will not break apart, minimizing a second chance of pollution.

18.6.8 Vibration

18.6.8.1 Present vibration design approaches

The traditional design methodology for vibration is based on rules, defined by classification societies. Vibrations are not explicitly covered by class rules but their prediction is needed to achieve a good design. Ship structures are excited by numerous dynamic oscillating forces. Excitation may originate within the ship or outside the ship by external forces. Reciprocating machinery such as large main propulsion diesel produce important forces at low frequency. Pressure fluctuations due to propeller at blade rate frequency induce pressure variation on the ship's hull. Varying hull pressures associated with waves belong also to external excitations. All these forces can be approximated by a combination of harmonic forces. If their frequencies coincide with the structure eigen frequencies, resonant behavior will happen.

It is of prime importance to avoid global main hull vibrations. If they do occur, the remedial action will probably be very costly. So, during early design, the hull girder frequencies must be compared to wave excitation (springing risk), and to propeller and engine excitation. Table 18.VI gives some typical values of the first hull girder frequencies in Hz of some ship types.

Hull girder frequencies and modes should be computed using approximate empirical formulae (88), simple beam models for long prismatic structures (VLCC, container ships, etc.) associated with lumped added mass models, or using 3D finite element models for complex ships (RO-RO, cruise ship), LNG, and short and non-prismatic structures (tug, catamaran, etc.).

18.6.8.2 Fluid structure interaction

Auid structure interaction is evidenced in the dynamic behavior of ships. As a first approximation, the ship is considered as a rigid body, for the sea keeping analyses (wave induced motions and loads).

Wave vibration induced: An early determination of hull girder vibration modes and frequencies is important to avoid serious problems that would be difficult to solve at a later stage of the project.

Risk of springing (occurring when first hull girder frequency equals wave encounter frequency) has to be detected very early. Springing may occur for long and/or flexible ships and for high speed craft and it increases the number of cyclic loads contributing to human fatigue. Various methods to assess the first hull girder frequency can be used at preliminary design stage.

Engine/propeller vibration induced: Resonance problems may also appear on small ships like tugs, where hull girder frequency can be close to the propulsion excitation (around 7Hz). High vibration levels contribute t'human fatigue and dysfunction, besides the discomfort aspect.

Fluid added mass: Hull girder vibrations induce displacement of the surrounding fluid. Therefore imparting kinetic energy in the fluid. This phenomenon can be taken into account for the hull girder modes and frequencies calculation as added mass terms. Various methods can be used for the determination of added mass term. Lumped mass approach is the simplest one (89) but is only valid for simple prismatic slender shapes, and for a single mode. Auid finite and semi-infinite elements or boundary integral formulation lead to the calculation of more accurate added mass matrices (90), especially for complex hull forms and appendices study (rudder). Added mass matrices associated with 3D finite element model of the structure, allow for an accurate determination of hull girder modes and frequencies. Added mass terms may also be needed for the vibrations of tank walls. The corresponding methods and associated software are available for industrial usage (Figure 18.54) and numerical simulations are today predictable with good accuracy (91). Figure 18.54 shows a fluid-structure coupled FE-model of a 230 m long passenger vessel using 150000 degrees of freedom.

A difficult coupled problem is the fluid impact occurring in slamming or due to sloshing in tanks. The local deformation of the impacted shells and plating influences the

TABLE 18.VI Typical Values of the First Hull Girder Frequencies (in Hertz)

Order (mode)	*Large Cruise ship*	*Fast monohull*	*LNG*	*VLCC*	*Frigate*	*Tug*
1	1.0 Hz	1.8	0.9	0.8	1.9	7.0
2	1.5 Hz	2.9	2.0	1.7	3.8	13
3	2.6 Hz	—	—	—	5.8	—
4	3.2 Hz	—	—	—	7.8	—

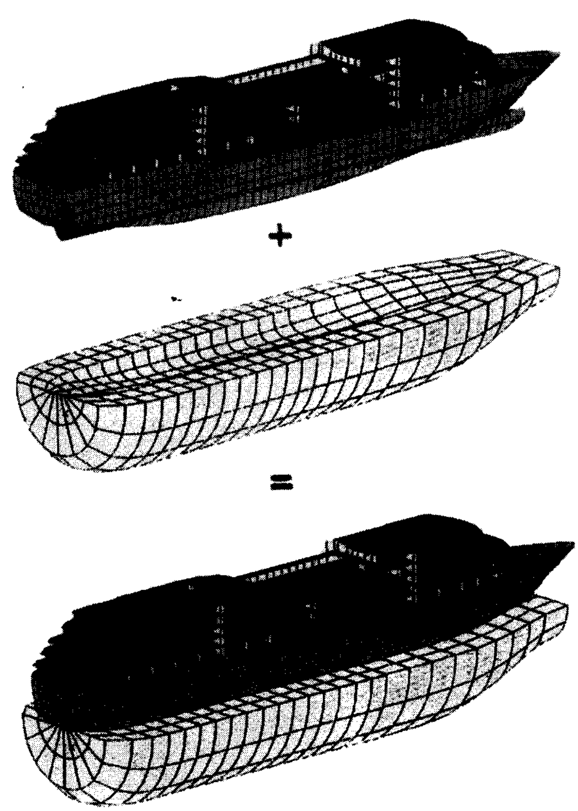

Figure 18.54 Fluid/Structure FE-Model of a Passenger Vessel (Principia Marine, France)

second action consists in avoiding resonance by modification of the hull scantlings, and addition of pillars, in order to increase or lower the eigen frequencies.

Reduction of unavoidable vibration levels can be achieved for local vibrations by dynamic isolation for equipments, passive damping solutions (floating floors on absorbing material), and dynamic energy absorbers. All these curative actions are usually difficult, costly, only applicable for local vibrations and nearly impossible for vibrations due to global modes. Local modes determination is difficult at early stage of the design mainly due to the uncertainty on mass distribution, non-structural mass (outfitting and equipments) being of the some order of magnitude as the steelwork part.

18.6.9 Special Considerations

In addition to the considerations for LNG tank, container ship, bulk carrier and passenger vessel, special considerations are available in Volume II of this book. Moreover, ISSC committees 1997 and 2000 also provide valuable information on specific ship types, that is, high-speed vessels and ships sailing in ice conditions.

18.6.9.1 LNG tanks

General information on such ships is available in Chapter 32 - Liquefied Gas Carriers. These ships contain usually a double hull (sides and bottom). Major structural concerns deal with the tanks themselves and with their support legs. Dilatation, tightness and thermal isolation are important aspects. There are several patented concepts: *independent tanks, membrane tanks, semi-membranes tanks* and *integral tanks.* Excepted for the *integral tanks,* the tanks are ~lf-supporting and are not essential to the hull strength. When supported by legs, these legs require a particular attention. Integral tanks form a structural part of the ship's hull and are influenced in the same manner by wave loads.

18.6.9.2 Container ships

The design of container ships of 5000 and 6000 TEU having a beam of 40m has increased the standard torsional problem of ships having a large open deck. Torsional strength and limitation of the equivalent stress (equation 45) at the hatch comers are the major issues in the evaluation of the strength of main hull structure. Use of multicell structures in side shell and double bottom is recommended. Moreover, the torsional moment distribution must be assessed with care.

As hatch covers are not considered as hull strength members, omission of hatch covers does not impose any particular effects in the structural design of a main hull structure. The general characteristics of container ships are detailed in Chapter 36 - Container Ships.

18.6.9.3 Bulk carriers

Casualty of bulk carriers was very high in the early 1990s. The main reasons were a lack of maintenance, excessive corrosion and fatigue (77). Weak point of these ships is the lower part of the side plate at the junction with the bilge hopper. Now, classification societies are aware about this problem and had updated their rules and associated structural details. The general design practice on bulk carriers is detailed in Chapter 33 - Bulk Carriers.

18.6.9.4 Passenger vessels

Ship strength analysis is based on a beam model. The complexity of large passenger ships, with a low resistant deck and wide openings, windows and openings in the side induces a much more complex behavior. Rational approach is necessary to get a realistic understanding of the flux of forces and capture the complex behavior of such ships. Due to the large openings and discontinuities, racking and stress concentration are two major concerns. For architectural reason, pillars are often omitted in large public areas (theater, lounge, etc.). Today, 3D FEA is usually carried out to design large passenger vessels (Figures 18.54 and 18.55). Due to large opening in the side shells, the vertical stress distribution is not linear (Figure 18.35). This means that the basic beam bending formulation is no valid (equation 29). More general information related to passenger vessels is available in Chapter 37 - Passenger Ships and in reference 68.

18.6.9.5 Composite material

Fiberglass boat building started in the 1960s. Today, designers are trying to plan composite construction of ships up to 100 meters in length. A comprehensive guide for the design of ship structures in composites is the Ship Structure Committee Report SSC-403 of Greene (96). Design methodology, materiel properties, micro and macro mechanic of composites and failures modes are deeply discussed.

In addition to the classic failure modes of steel and aluminum structures presented in Subsection 18.6.1, composites are subject to specific failure modes.

In compression, there are the *crimping, skin wrinkling* and *dimpling* of the honeycomb cores (Figure 18.56). In bending, instead of the traditional first yield bending moment, for composites, the design limit load corresponds to the *first ply failure.*

The *creep* behavior and *the long-term damage* from water, UV and temperature, and their performance in fires are other specific structural problems of composites. A review of the performance of composite structures is proposed by Jensen et al (98).

18.6.9.6 Aluminum structures

Compared to steel, the reduced specific weight of aluminum (2.70 kN/m^3 for aluminum and 7.70 kN/m^3 for steel) is a very interesting property for a ship designer. The yield stress of unwelded aluminum alloys can be comparable to mild steel (235 MPa) but changes drastically from one alloy to another (125 MPa for ALU 5083-0 and 215 MPa for ALU 5083-H321). The modulus of elasticity of aluminum alloys is one-third of steel.

The main difficulty for the use of aluminum use deals with its mechanical properties after welding. The yield stress of aluminum alloys may decrease significantly after welding (remains at 125 MPa for

ALU 5083-0 but drop to 140 MPa for ALU 5083-H321). The area close to a weld is called *Heat Affected Zone* (HAZ). It is characterized by reduced strength properties. HAZ is particularly important to assess the buckling and ultimate strength of welded components such as beam~column elements, stiffened panels, etc.

For marine applications ALU 5083, 5086 and 6061 can be used. Nevertheless, the mechanical and strength properties of aluminum change a lot with the alloy composition and the production processing. Thus, the alloy selection must be done with care with regard to the yield strength before and after welding, the welding and extruding capabilities, the marine behavior, etc.

Fire strength is another concerns when using aluminum alloys as it quickly loses its strength when the temperature rises. **t**

Despite the aforementioned shortcomings aluminum alloys will be more extensively use in the future for the design of fast vessels, for which the structural weight is very important to reach higher speed (for high speed mono hull, catamaran and trimaran vessels). The good extruding capability of aluminum alloys has to be enhanced through scantling standardization. That helps to lower to production cost ($/man-hour) and compensate the initial higher material cost of aluminum, which is approximately 3 times higher that mild steel ($/kg).

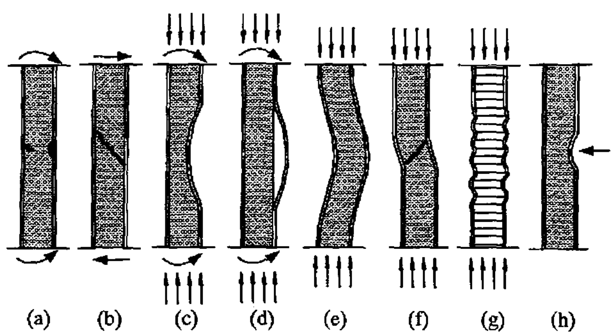

Figure 18.56 Potential Failure Modes of Sandwich Panels (100), (a) Face yielding/fracture, (b) Core shear failure, (c-d) Face wrinkling, (e) Buckling, (f) Shear crimping, (g) Face dimpling, (h) Local indentation.

18.6.9.7 Corrosion

Corrosion does not present a structural design problem, as almost all the classification societies base their rules on a *net scantling.* This means that the thickness to consider in analysis (for empirical formulations up to complex PEA) is the reduced thickness (without corrosion allowance) and not the actual thickness. The difference between the reduced thickness and the actual one is usually fixed by the classification but can also change according to the owner requirements. This is an economic choice and not a structural problem.

For bulk carriers, thickness reduction due to corrosion is generally assumed to be 5 mm for hold frames and 3 mm for side shell plating.

18.7 NUMERICAL ANALYSIS FOR STRUCTURAL DESIGN

18.7.1 Motivation for Numerical Analysis

In most of the cases, a ship is a one of a kind product, even if limited series may exist in some cases. The design, study and production cycle is very short and major decision have to be taken very early in the project. It is well known that the cost of a late modification is very high and such a situation has to be avoided. Also experience-based design can be an obstacle to the introduction of innovation. Numerical analysis clearly is needed to improve the design (innovation) but also to control safety margins. Moreover, it gives access to local and detailed analysis, which is not possible with simplified methods. The concept of numerical mock up, used in aerospace and car industry has proven its efficiency. Shipbuilding is clearly moving in the same direction.

18.7.1.1 Static and quasi-static analysis

Static and quasi-static analysis represents the traditional way to perform stress and strength analysis of a ship structure. Loads are assessed separately of the strength structure and, even if their origins are dynamic (flow induced), they are assumed to be static (do not change with the time). This assumption may be correct for the hydrostatic pressure but not when the dynamic wave loads are changed to static loads applied on the side plates of the hull.

In the future, even if the assumption of static loads is not verified, static analysis will continue to be performed, as it is easier and faster to perform. In addition, tens of experience years have shown that they provide accurate results when stresses and deflections assessment are the main target (as defined in Section 18.4).

Such analysis is also the standard procedure for fatigue assessment to determine the hot spot stress through fine mesh PEA.

18.7.1.2 Dynamic analysis

When problems occur on a ship due to dynamic effects, it is very often late in the design and building stage and even in service, and corrective actions are costly. Simplified methods can only predict the first hull girder modes frequencies. Numerical finite element based simulation is mature enough to predict up to second propeller harmonic, the vibration level, giving a design tool to comply with ISO or ship owner requirements. Moreover, possible dynamic problems can be detected early enough in the design to allow for corrective actions.

18.7.1.3 Nonlinearities analysis

Nonlinear structural analysis is mainly used to analyze buckling, ultimate strength and accidental or extreme situations (explosions, collisions, grounding, blast). The results of such costly and difficult analysis are often used to calibrate simplified methods or rules. But they are also very useful to understand possible failure modes and mechanical behavior under severe loads.

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18.7.1.4 Emerging trends

Like the automotive and aerospace industry, there is a clear trend towards the reduction of design cycle time. Numerical mock up or virtual ship approach (97), especially for one of a kind product, is clearly a way to achieve this. Required computing power is available and will no longer be a constraint. The first difficulty is to establish an *efficient* model of complex physical problems, associated with increasing demand for accuracy. The second difficulty is the manpower needed to prepare and check the models, which will be solved by the development of integrated solutions for ship description and modeling (99).

Advances are expected in the field ofPE-modeling. The trend is toward one structure description, one model and several applications. This is the field for multiphysics and coupling analysis. The base modeling will be re-used and adapted to perform successively,

- static, fatigue and fracture analysis,
- buckling and ultimate strength analysis,
- vibration and acoustics analysis, and
- vulnerability assessment.

Progress is expected by the utilization of reliability methods already used in offshore industry, where uncertainties and dispersions of the loads, geometrical defaults, initial stresses and strains, material properties are defined as stochastic (non deterministic) data, leading to the calculation of a probability of failure. This philosophy can be applied to fatigue and ultimate strength, but also to dynamic response, leading to a more robust design, less sensitive to defaults, imperfections, uncertainties and stochastic nature ofloads. Reliability-based analyses using probabilistic concept are presented in Chapter 19.

In the future, safety aspects related to structural problems will also be tackled such as ultimate strength using nonlinear methods. Collision and grounding damages and improved design to increase ship safety will be studied by numerical simulation, whereas experimental approach is nearly impossible and/or too costly. Explicit codes, used in car crash simulation (101), will be adapted to specific aspects of ship structure (size and presence of fluid). In traditional sea keeping analysis, the ship is considered as a rigid body. In coupled problems such as slamming situations, this hypothesis is no more valid and a part of the energy is absorbed by ship deformation. Hydro-elasticity methods (102) aim taking into account the interaction of the flexible ship structure with the surrounding water. Nonlinear effects due to bow and aft part of the ship, ship velocity, diffraction radiation effects contribute to the complexity of the problem. The simulation of catamaran, trimaran and fast monohulls behavior need the development of new methods to take into account the high velocities and the complex 3D phenomena.

18.7.2 Finite Element Analysis

The main aim of using the finite element method (FEM) in structural analysis is to obtain an accurate calculation of the stress response in the hull structure. Several types or levels of FE-models may be used in the analyses:

- global stiffness model,
- cargo hold model,
- frame and girder models,
- local structure models, and
- stress concentration models.

The model or sets of models applied is to give a proper representation of the following structure:

- longitudinal plating,
- transverse bulkheads/frames,
- stringers/girders, and
- longitudinals or other structural stiffeners.

The finer mesh models are usually referred to as sub-models. These models may be solved separately by transfer of boundary deformations/ boundary forces from the coarser model. This requires that the various mesh models are *compatible,* meaning that the coarser models have meshes producing deformations and/or forces applicable as boundary conditions for the finer mesh models.

18.7.2.1 Structural finite element models

Global stiffness model: A relatively coarse mesh that is used to represent the overall stiffness and global stress distribution of the primary members of the total hull length. Typical models are shown in Figure 18.57. The mesh density of the model has to be sufficient to describe deformations and nominal stresses from the following effects:

- vertical hull girder bending including shear lag effects,
- vertical shear distribution between ship side and bulkheads, ,
- horizontal hull girder bending including shear lag effects, torsion of the hull girder, and
- transverse shear and bending.

Stiffened panels may be modeled by means of layered elements, anisotropic elements or frequently by a combination of plate and beam elements. It is important to have a good representation of the overall membrane panel stiffness in the longitudinal/transverse directions. Structure not contributing to the global strength of the vessel may be disregarded; the mass of these elements shall nevertheless be included (for vibration). The scantling is to be mode_d with *reduced scantling,* that is, corrosion addition is to be deducted from the actual scantling.

All girder webs should be modeled with shell elements. Flanges may be modeled using beam and truss elements. Web and flange properties are to be according to the real geometry.

The performance of the model is closely linked to the type of elements and the mesh topology that is used. As a standard practice, it is recommended to use 4-node shell or membrane elements in combination with 2-node beam or truss elements are used. The shape of 4-node elements should be as rectangular as possible as skew elements will lead to inaccurate element stiffness properties. The element formulation of the 4-node elements requires all four nodes to be in the same plane. Double curved surfaces should therefore not be modeled with 4-node elements. 3-node elements should be used instead.

The minimum element sizes to be used in a global structural model (coarse mesh) for4-node elements (fin,er mesh divisions may of course be used and is welcomed, specially with regard to sub-models):

- main model: 1 element between transverse frames/girders; lelement between structural deck levels and minimum three elements between longitudinal bulkheads,
- girders: 3 elements over the height, and
- plating: 1 element between 2 longitudinals.

Cargo hold model: The model is used to analyze the deformation response and nominal stresses of the primary members of the midship area. The model will normally cover 1/2+ 1+ 1/2 cargo hold/tank length in the midship region. A typical model is shown in Figure 18.58.

Frame and girder models: These models are used to analyze nominal stresses in the main framing/girder system (Figure 18.59). The element mesh is to be fine enough to describe stress increase in critical areas (such as bracket with continuous flange). This model may be included in the cargo hold model, or run separately with prescribed bound-

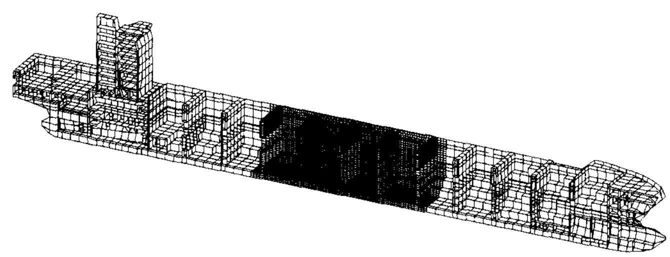

Figure 18.57 Global Finite Element Model of Container Vessel Including a 4 Cargo Holds Sub-model (4).

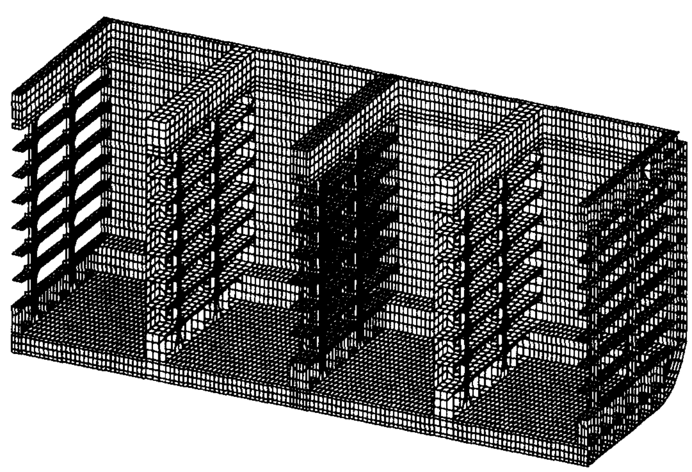

Figure 18.58 Cargo Hold Model (Based on the Fine Mesh of the Frame Model), (4)

ary deformations/forces. However, if sufficient computer capacity is available, it will normally be convenient to combine the two analyses into one model.

Local structure analyses are used to analyze stresses in local areas. Stresses in laterally loaded local plates and stiffeners subjected to large relative deformations between girders/frames and bulkheads may be necessary to investigate along with stress increase in critical areas, such as brackets with continuous flanges.

As an example, the areas to model are normally the following for a tanker:

- longitudinals in double bottom and adjoining vertical bulkhead members,
- deck longitudinals and adjoining vertical bulkhead members,
- double side longitudinals and adjoining horizontal bulkhead members,
- hatch comer openings, and
- corrugations and supporting structure.

The magnitude of the stiffener bending stress included in the stress results depends on the mesh division and the element type that is used. Figure 18.60 shows that the stiffener bending stress, using FEM, is dependent on the mesh size for 4-node shell elements. One element between floors results in zero stiffener bending. Two elements between floors result in a linear distribution with approximately zero bending in the middle of the elements.

Stress concentration models are used for fatigue analyses of details were the geometrical stress concentration is unknown. A typical detail is presented Figure 18.61.

Local FE analyses may be used for calculation of local geometric stresses at the hot spots and for determination of associated K-factors to be used in subsequent fatigu~ analyses (equation 63). The aim of the FE analysis is n~rmally not to calculate directly the notch stress at a detail, but to calculate the geometric stress distribution in the region of the hot spot. These stresses can then be used either directly in the fatigue assessment of given details or as a basis for derivation of stress concentration factors. FE stress concentration models are generally very sensitive to element type and mesh size.

Several FEA benchmarks of such structural details were performed by ISSC technical committees (68,103). They assess the uncertainties of different FE packages associated with coarse and fine mesh models. Variation is usually around 10% but is sometime much larger.

This implies that element sizes in the order of the plate thickness are to be used for the modeling. If solid modeling is used, the element size in way of the hot spot may have to be reduced to half the plate thickness in case the

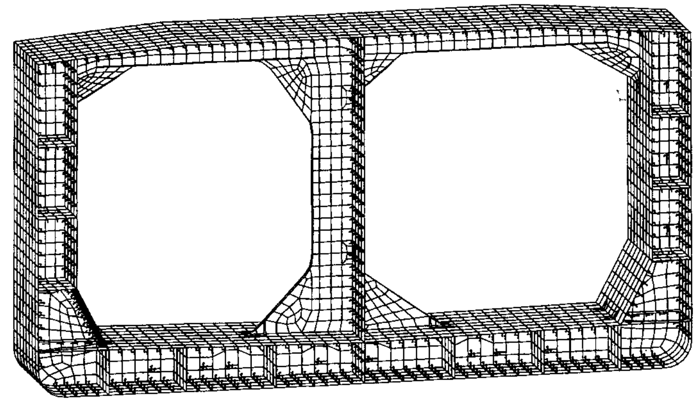

Figure 18.59 Frame and Girder Model (Web Frame), (4)

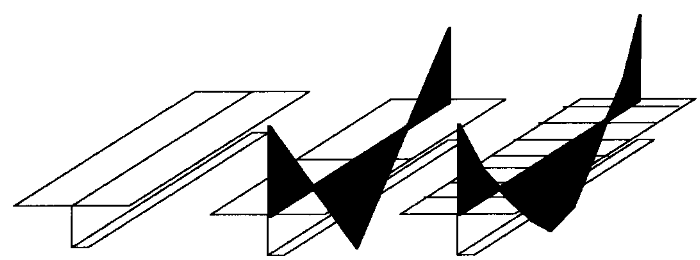

Figure 18.60 Stiffener Bending Stress with FEM (from left to right: using 1, 2 or 8 elements), (4)

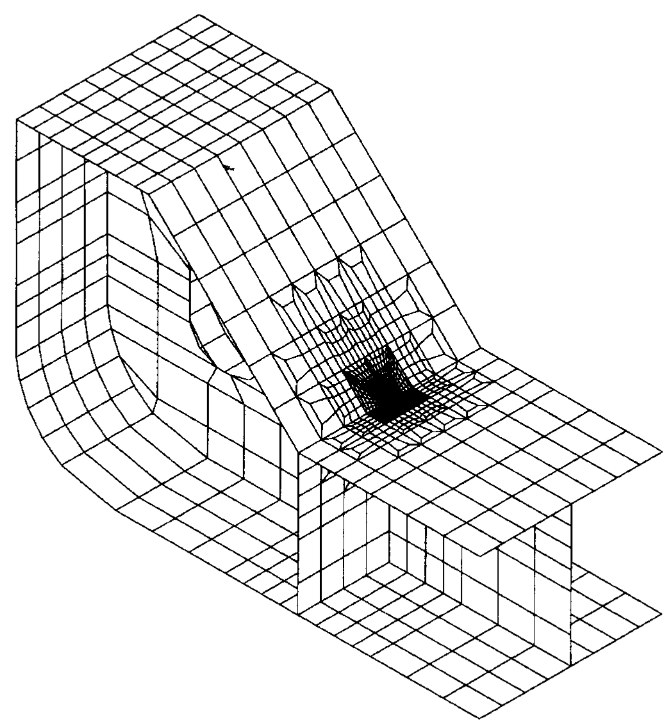

Figure 18.61 Stress Concentration Model of Hopper Tank Knuckle (4)

Since the publication of an early book on BEM, many engineering applications using BEM have been achieved. More recent developments of BEM together with the basic idea may be found in Brebbia and Dominguez (109). While there are some problem areas to overcome in use of BEM for non-linear analysis, it has been recognized that BEM is a powerful alternative to FEM particularly for problems involving stress concentration or fracture mechanics, and for cases in which the integral domain extends to infinity. For example, to design the cathodic corrosion protection systems for ships, offshore structures and pipelines, it has been suggested that BEM should be employed, with the region of interest extending to infinity. BEM can also be applied to problems other than stress or temperature analysis, including fluid flow and diffusion (for example, for fluid-structure interaction, Subsection 18.6.8.2).

Main advantages ofBEM are due that very complex expressions of integral equations can be adopted, resulting in higher accuracy of the results.

In this regard, BEM can be involved in the usage of more refined mathematical treatment than FEM. However, to calculate the integral equations using BEM, appropriate numerical techniques should be used, otherwise the integration results may not be accurate. For most linear problems, linear or *flat* boundary elements along the boundary of the integral domain can be used so that we don't have to carry out numerical integration. If *analytical solutions* are available the required computing times will be very small and the accuracy high. Nevertheless as the required comp'lltational times with the BEM is in general significant, BEM may be more appropriate for linear analysis of solids and for fluid mechanics problems.

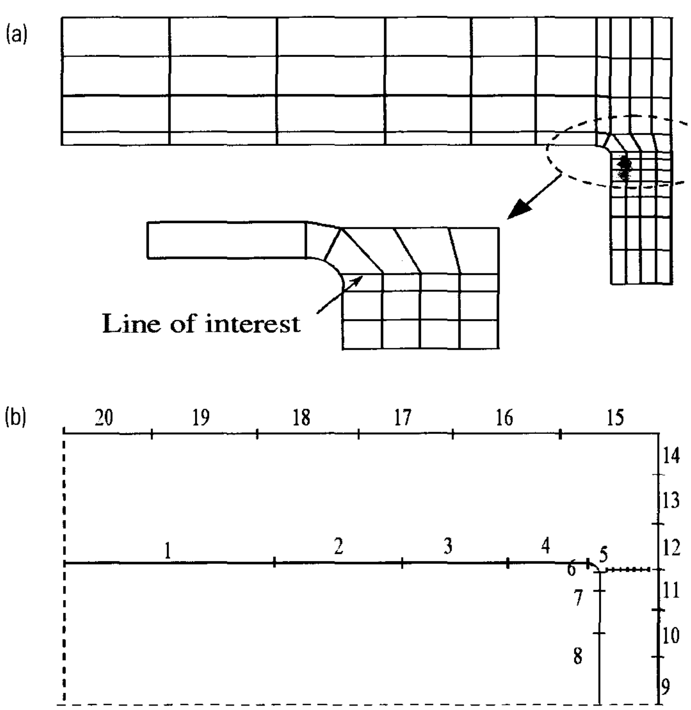

Figure 18.65 A Typical FEM/BEM Model for Analysis of the Pressure Vessel (109). (a) Typical BEM model, and (b) Typical FEM model.

18.7.4 Presentation of the Stress Result

After performing an analysis, the presentation of the stress and deformation is very important. It should be based on *stresses* acting at the middle of element thickness, excluding plate-bending stress, in the form of ISO-stress contours in general. Numerical values should also be presented for highly stressed areas or locations where openings are not included in the model.

The following results should be presented for parts of the vessel covered by the global model, such as, cargo hold model and frame and girder models:

- deformed shape for each loading condition,
- In-plane maximum normal stresses (*ax* and ay) in the global axis system, shear stresses (1) and equivalent von Mises stress (a_e) of the following elements:
  - bottom,
  - inner bottom,
  - deck,
  - side shell,
  - inner side including hopper tank top,
  - longitudinal and transverse bulkheads, and
  - longitudinal and transverse girders.
- Axial stress of free flanges,
- Deformations of supporting brackets for main frames including longitudinals connected to these when applicable,
- Deformation of supports for longitudinals subject to large relative deformation when applicable.

For parts of the vessel covered by the local model, the following stresses are to be presented:

- Equivalent stress of plate/membrane elements,
- Axial stress of truss elements,
- Axial forces, bending moments and shear forces for beam elements.

18.7.5 Relevant Structural Analysis Methods for Specific Design Stages

Shipbuilding design offices face very challenging situations (especially for passenger and other complex ships). The products are one-of-a-kind or at least on short series and the resulting ships are designed and built within two years for 20 to 30 years of operation. Another impact on design activities that is also challenging is that the design overlaps the production. To clarify the actual situation, a common view of the design workflow for a commercial ship in the shipyard is shown in Table 18.VII.

18.7.5.1 Basic design

The *Basic Design* is the design activities performed before order. This phase does not overlap with the production but is very short and will become the technical basis for the contract. The shipyard must be sure that no technical problem will appear later on, to avoid extra costs not included in the contract. The structural analysis carried out in this phase must be as fast as possible because the allocated time is short. The most time consuming task for analysis is the data input. The more detailed are the data more accurate the results. There are three kinds of early analysis:

1. *First principles methods:* Very simplified geometric representation of the structure. These methods are dedicated to an assessment of the global behavior of the ship. They mainly use empirical or semi-empirical formulas.

TABLE 18.VII Timing of a Design Project

Basic Design	
Concept Design	*1 or 2 days*
Preliminary Design	*About 1 week*
Contract Design	*Months*
Receive Order	
Production Design	
Complete Functional Design	*1 or 2 months*
Production Design	*6–10 months*

TABLE 18.VIII Classification Society Tools Overview (110)

Classification Society	*Product*
American Bureau of Shipping (ABS)	ABS Safe Hull
Bureau Veritas (BV)	VeriSTAR
Det Norske Veritas (DNV)	Electronic Rulebook & Nauticus HULL
Germanisher Lloyd (GL)	GL-Rules & POSEIDON
Korean Register of shipping (KRS)	KR-RULES, KR-TRAS
Lloyd's Register of Shipping (LR)	Rulefinder, ShipRight
Nippon Kaiji Kyokai (NK)	PrimeShip BOSUN

2. *Two-dimensional (or almost 2D) geometry-based methods:* These methods are based on one or more 2D views of the ship sections. The expected results may be:

   • Verification of main section scantlings,
   • Global strength assessment,
   • Global vibration levels prediction,
   • Ultimate strength determination, and
   • Early assessment of fatigue

   Two main approaches exist:

   a. The main section of the ship is modeled a 2D way (including geometry and scantlings) then global, and possibly local, loadings are applied (bending moments, pressures, etc.). All major Classification Societies provide today the designer with such tools (Table 18.VIII).
   b. Various significant sections are described as beam cross section properties (areas, inertias, etc.) and then the ship is represented by a beam with variable properties on which global loading is applied.

3. *Simple three-dimensional models:* These models are useful when a more detailed response is needed. The idea is to include main surfaces and actual scantlings (or from the main section when not available) in a 3D model that can be achieved in one or two weeks. This approach is mainly dedicated to novel ship designs for which the feedback is rather small.

18.7.5.2 Production design

The most popular method for structural analysis at the production design stage remains the Finite Elements Analysis (FEA). This method is commonly used by Shipyards, Classification Societies, Research Institutes and Universities. It is very versatile and may be applied to various types of analysis:

- global and local strength,
- global and local vibration analysis (natural frequencies with or without external water, forced response to the propeller excitation, etc.),
- ultimate strength, and
- detailed stress for local fatigue assessment,
- fatigue life cycle assessment,
- analysis of various non-linearities (material, geometry, contact, etc.), and
- collision and grounding studies.

The two main approaches for solving the physical problem are:

1. implicit method is used to solve large problems (both linear and non linear) with a matrix-based method. This is the favored method for solving global and local linear strength and vibration problems. But it can also be ap-

plied to non linear calculations when the time step remains rather large (about 1/10 to 1 second), and
2. explicit method is mainly used for fast dynamics (as collision and grounding or explosion) where time step is quite smaller. This method allows using different formulations for structural elements (Lagrangian) and fluid elements (Eulerian).

One interesting result from research that is being introduced today is the reliability approach (see Chapter 19). This approach introduces uncertainties within the model (non planar plates, residual stresses from welding, discrepancies in the thickness ...) to provide the designer with a level of reliability for a given result instead of a deterministic value.

For FEA models, the modeling time is usually assumed to be 70% of the overall calculation time and results exploitation 30%. The computation itself is regarded as negligible (excepted for explicit analysis). *So the main efforts today are focused on reducing the modeling time.*

18.7.6 Optimization

Optimization is a field in which much research has been carried out over a long time. It is included today in many software tools and many designers are using it. The aim of optimization is to give the designers the opportunity to change design variables (such as thickness, number and cross section of stiffeners, shape or topology) to design a better structure for a given objective (lower weight or cost).

Optimization can be performed both at basic and production design stages:

- *Basic Design:* Even with simplified models, the designer can optimize the scantlings. It can be used for instance to find out the minimal scantlings for a novel sljp for which the yard have a lack of feedback, .
- *Production Design:* Optimization can be used for three main purposes:

1. Scantlings optimization, which gives the user the minimum scantlings for a given structure. The number of longitudinals and the frame spacing for a given cargo hold/tank can also be optimized (105).
2. Shape optimization (111), which uses a given topology and scantlings to provide the user the minimum, required area of material (reducing holes in a plate for instance), and to improve the hull shape considering the fluid-structure interaction.
3. Topology optimization (112) which uses a given scantlings and allows the user to find out where to put material. An academic example of topology optimization is given on Figure 18.66.

Weight is the most usual objective function for structure optimization. Minimizing weight is of particular importance in deadweight carriers, in ships required to haye a limited draft, and in fast fine lined ships, for example, passenger vessels. However, it is well know that the lowest weight solution is not usually the lowest acquisition cost. Today, cost is becoming the usual objective function for optimization (124).

For the other ship types it is still desirable to minimize steel weight to reduce material cost but only when this can be done without increasing labor costs to an extent that exceeds the saving in material costs. On the other hand, a reduction in structural labor cost achieved by simplifying construction methods may still be worthwhile even if this is obtained at the expense of increasing the steel weight.

Rigo (105) presents extensive review of ship structure optimization focusing on scantling optimization. Vanderplaats (113), and Sen and Yang (114) are standard reference books about optimization techniques. Catley et al (115), Hughes (3) and Chapter 11 of this book also contain valuable information on structure optimization.

18.7.6.1 Scantling optimization procedure

A standard optimization problem is defined as follows:

- X_i (i = 1, N), the N design variables,
- F(X), the objective function to minimize,
- $C_j(X) \sim CM_j$ (j = 1, M), the M structural and geometrical constraints,
- $X_{i\,min} \sim X_i \sim X_{i\,max}$ upper and lower bounds of the X_i design variables: technological bounds (also called *side constraints)* .

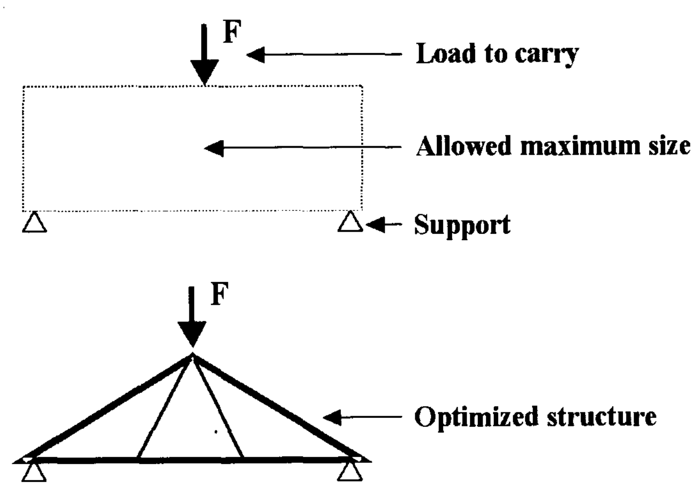

Figure 18.66 Topology Optimization

Constraints are linear or nonlinear functions, either explicit or implicit of the design variables (XI). These constraints are analytical translations of the limitations that the user wants to impose on the design variables themselves or to parameters like displacement, stress, ultimate strength, etc. Note that these parameters must be functions of the design variables.

So it is possible to distinguish:

Technological constraints (or side constraints) that provide the upper and lower bounds of the design variables. For example:

$$X_{i\ min} = 4mm \le X_i \le X_{i\ max} = 40\ mm,$$

with:

$X_{i\ min}$ = a thickness limit dues to corrosion,
$X_{i\ max}$ = a technological limit of manufacturing or assembly.

Geometrical constraints that impose relationships between design variables in order to guarantee a functional, feasible, reliable structure. They are generally based on *good practice* rules to avoid local strength failures (web or flange buckling, stiffener tripping, etc.), or to guarantee welding quality and easy access to the welds. For instance, welding a plate of 30 mm thick with one that is 5 mm thick is not recommended. Hence, the constraints can be $0.5 \le X2 / X1 \le 2$ with X1, the web thickness of a stiffener and X2, the flange thickness.

Structural constraints represent limit states in order to avoid yielding, buckling, cracks, etc. and to limit deflection, stress, etc. These constraints are based on solid-mechanics phenomena and modeled with rational equations. Rational equations mean a coherent and homogeneous group of analysis methods based on physics, solid mechanics, strength and stability treatises, etc. and that differ from empirical and parametric formulations. Such standard rational structural constraints can limit:

- the deflection level (absolute or relative) in a point of the structure,
- the stress level in an element: σ_x, σ_y, and $\sigma_c = \sigma_{von\ Mises}$,
- the safety level related to buckling, ultimate resistance, tripping, etc. For example: $\sigma / \sigma_{ult} \le 0.5$.

For each constraint, or solid-mechanics phenomenon, the *selected behavior model* is especially important since this model fixes the quality of the constraint modeling. These behavior models can be so *complex* that it is no longer possible to explicitly express the relation between the parameters being studied (stress, displacement, etc.) and the design variables (XI). This happens when one uses mathematical models (FEM, ISUM, BEM, etc.). In this case, one generally uses a numeric procedure that consists of replacing the implicit function by an explicit *approximated function* adjusted in the vicinity of the initial values of the design variables (for instance using the first or second order Taylor series expansions). This way, *the optimization process becomes an iterative analysis* based on a succession of local approximations of the behavior models.

At least one constraint should be defined for each failure mode and limit state considered in the Subsection 18.6.1. When going from the *local* to the *general* (Figure 18.38), there are three types of constraints: 1) constraints on stiffened panels and its components, 2) constraints on transverse frames and transversal stiffening, and 3) constraints on the global structure.

Constraints on stiffened panels (Figure 18.22): Panels are limited by their lateral edges (junctions with other panels, AA' and BB') either by transverse bulkheads or transverse frames. These panels are orthotropic plates and shells supported on their four sides, laterally loaded (bending) and submitted, at their extremities, to in-plane loads (compression/tensile and shearing).

Global buckling of panels (including the local transverse frames) must also be considered. Panel supports, in particular those corresponding to the reinforced frames, are assumed infinitely rigid. This means that they can distort themselves significantly only after the stiffened panel collapse.

Constraints on the transverseframes (Figure 18.23): The frames take the lateral loads (pressure, dead weight, etc.) and are therefore submitted to combined loads (large bending and compression). The rigidity of these frames must be assured in order to respect the hypotheses on panel boundary conditions (undeformable supports).

Constraints on the global structure (box girder/hull girder) (Figure 18.46): The ultimate strength of the global structure or a section (block) located between two rigid frames (or bulkheads) must be considered as well as the elastic bending moment of the hull girder (against yielding).

18.8 DESIGN CRITERIA

In ship design, the structural analysis phase is concerned with the prediction of the magnitude of the stresses and deflections that are developed in the structural members as a result of the action of the sea and other external and internal causes. Many of the failure mechanisms, particularly those that determine the ultimate strength and collapse of the structure, involve non-linear material and structural behavior that are beyond the range of applicability of the linear structural analysis procedures in Section 18.4, which are commonly used in design practice. Most of the available methods of non-linear structural analysis are briefly introduced in Sections 18.6 and 18.7. Sometimes, these methods are limited in their applicability to a narrow class of problems.

One of the difficulties facing the structural designer is that linear analysis tools must often be used in predicting the behavior of a structure in which the ultimate capability is governed by non-linear phenomena. This is one of the important sources of uncertainty related to strength assessment.

After performing an analysis, the adequacy or inadequacy of the member and/or the entire ship structure must then be judged through comparison with some kind of criterion of performance *(Design Criteria).* The conventional criteria that are commonly used today in ship structural design are usually stated in terms of acceptable levels of stress in comparison to the yield or ultimate strength of the material, or as acceptable stress levels compared to the critical buckling strength and ultimate strength of the structural member. Such criteria are, therefore, intended specifically for the prevention of yielding (hull girder, frames, longitudinals, etc), plate and stiffened plate buckling, plate and stiffened plate ultimate strength, ultimate streng!h of hull girder, fatigue, collision, grounding, vibration and many other failure modes specific to particular vessel types. Information related to the design criteria is given in Section 18.6 for each specific failure mode (see also Beghin et al (116)).

18.8.1 Structural Reliability as a Design Basis

Three categories of design methodology are basically available. They are usually classified as:

1. deterministic method,
2. semiprobabilistic method, and
3. full probabilistic method.

The deterministic method uses a global safety factor. It assumes that loads and strength are fully determined. This means that no aspect of randomness is considered. Everything is assumed to be deterministic. The global safety factor is compared to the ratio between the actual strength and the required strength.

The full probabilistic method is an ideal approach assuming that all the randomness can be exactly considered within a global probabilistic approach. All the actual development in structural reliability and reliability analysis show the huge effort actually done to reach that aims. Chapter 19 presents in detail the reliability concept with examples of the reliability-based strength analysis of plates, stiffened panels, hull girder and fatigue. See also Mansour et al (42).

The semiprobabilistic method corresponds to the current practice used by codes and the major classifications societies. Load, strength, dimensions are random parameters but their distribution is basically not known. To overcome this, partial safety factor are used. Each safety factor corresponds to a load type, failure mode, etc. This is an intermediate step between the deterministic and the full probabilistic methods.

18.9 DESIGN PROCEDURE

It does not seem possible to unify all of the design procedures (117-122). They differ from country to country, from shipyard to shipyard and differ between naval ships, commercial ships and advanced high-speed catamaran passenger vessels. So, as an example of one feasible methodology, the design procedure for commercial vessel such as tanker, container, and VLCC is selected. It corresponds to the actual current shipyard procedure.

This structural design procedure can be defined as follows:

- receive general arrangement from the basic design group,
- define structural arrangement based on the general arrangement,
- determine initial scantling of structural members within design criteria (rule-based).,
- check longitudinal and transverse strength,
- change the structural arrangement or scantling, and
- transfer the structural arrangement and scantling to the production design group.

The structural design can also be classified according to available design tool:~

- use data of existing ship or past experience--expert system, (1st level)
- use of a structural analysis software like FEM (2nd level)
- use optimization software (3rd level)

The adequacy of the relevant analysis method to use for a specific design stage is discussed in Subsection 18.7.5. Here the discussion concerns the procedure from a *design point of view* and not from the *analysis point of view.*

18.9.1 Initial Scantling

At the basic design stage, principal dimensions, hull form, double bottom height, location of longitudinal bulkheads and transverse bulkheads, maximum still-water bending moment, etc. have already been determined to meet the owner's requirements such as deadweight and ship's speed. Such a parametric design procedure presented in Chapter 11 is relevant for this stage.

For the structural design stage, the structural arrangement is carried out to define the material property, plate breadth, stiffener spacing, stiffener type, slot type, shape of openings, and frame spacing. The initial scantling of longitudinal members such as plate thickness and section area of stiffener can be determined by applying the classification rules which give minimum required value to meet the bending, shear and buckling strength. As there are usually no suitable rules for the transverse members, the initial scantling of transverse members such as height and thickness of web, breadth and thickness of flange are determined by reference to similar ships or using empirical shipyard database.

18.9.2 Strength Assessment

The purpose ofthe strength assessment is to validate the initial design, that is, to evaluate quantitatively the strength capability of the initial design. This problem was extensively presented in previous Sections 18.4, 18.5 and 18.6.

In general, the longitudinal members are subjected to several kinds of stresses in the sea-going condition: primary, secondary and tertiary stresses (Subsection 18.4.1). As all these stresses act simultaneously, the superposition of these stresses should not exceed the allowable equivalent stress given by the classification rules (equations 45 and 46).

There are two kinds of strength to design the longitudinal members. One is the local strength to avoid collapse, and the other is the longitudinal strength to consider the collapse of the ships' hull girder. The local strength is automatically satisfied if the design is based on the classification rules. The hull girder longitudinal strength ca¥e assessed with the hull section modulus (SM) at bottom and deck where the extreme stresses are taken place (equation 29). The hull section modulus is calculated easily by using available software.

If the hull section modulus at bottom or deck part is bigger than the required value, this design can be considered as finished but this design might be too expensive. If the section modulus at the deck or at the bottom is less than the required value, the designer should change the initial scantlings.

If the calculated hull section modulus at deck part is less than required, he can increase, step by step, the deck scantling (for example, 0.5 mm for the plate thickness) until the requirement is satisfied.

The designer also has to modify the scantling (usually plate thickness) of transverse members, for which the stress exceeds the allowable value. The designer estimates the increased thickness according to the difference between the actual stress and allowable stress. If the difference is small, it is not necessary to perform a new strength assessment and the design may be completed with only small changes. If the difference is large, the design should be drastically changed and it will be necessary to analyze the structure again (see previous step in this Subsection).

Then, the designer has to check the transverse strength by comparing the actual stresses in the transverse frames with the allowable stresses given by the classification rules. The actual stresses such as equivalent stress and shear stress can be obtained using commercial FEA packages. If the stress in some of elements exceeds the allowable stress, the designer should increase the initial scantling. These changes are performed at the third step *Structural Design* using the results of the *Strength Assessment* and by comparison with the design criteria.

18.9.3 Structural Design

If all of local scantlings are determined by the rule minimum values, and if the longitudinal strength satisfies the rule strength requirement, the design is completed. But, even if this design is strong enough, it might be too heavy and/or too expensive and it should be refined. In practice, refining an already feasible design is a difficult task and requires experience. The designer can change the structural arrangement, especially the dimensions such as frame spacing, and material properties to better fit with the longitudinal strength requirements. This work has to be done in agreement with the basic design team.

Instead of the trial and error procedure discussed above, an automatic optimization technique can be used to obtain the minimum weight and/or cost for the longitudinal and transverse structural member. The object function(s) can be structural weight and/or fabrication cost, using either a single object function approach or a multiple objective function method. The design variables can be longitudinal and transverse spacing, deck/bottom scantlings for the longitudinal and transverse members (web height and thickness, flange width and thickness). The constraints and limitations of the optimization process can be the range of each design variable as well as the required hull section modulus and minimum deck/bottom scantlings for the longitudinal members, and allowable bending and shear stresses for the transverse members (see *Optimization* in Subsection 18.7.6).

18.9.4 A Generic Design Framework

By comparison with the previous standard procedure, Figure 18.67 shows a new *generic* and advanced design methodology where the performance of the system, the manufacturing process of the system and the associated life cycle costs are considered in an integrated fashion (120). Designing ship structures systems involves achieving simultaneous, though sometimes competing, objectives. The structure must perform its function while conforming to structural, economic and production constraints. The present design framework consists of establishing the structural system and composite subsystems, which optimally satisfy the topology, shape, loading and performance constraints while simultaneously considering the manufacturing or fabrication processes in a cost effective manner.

The framework is used within a computerized virtual environment in which CAD product models, physics-based models, production process models and cost models are used simultaneously by a designer or design team. The performance of the product or process is in general judged by some time independent parameter, which is referred to as a response metric (R). Specifications for the system must be established in terms of these Response Metrics. The formulation of the design problem is thus the same whether the product or process systems (or both) are considered.

The general framework consists of a system definition module, a simulation module and a design module.

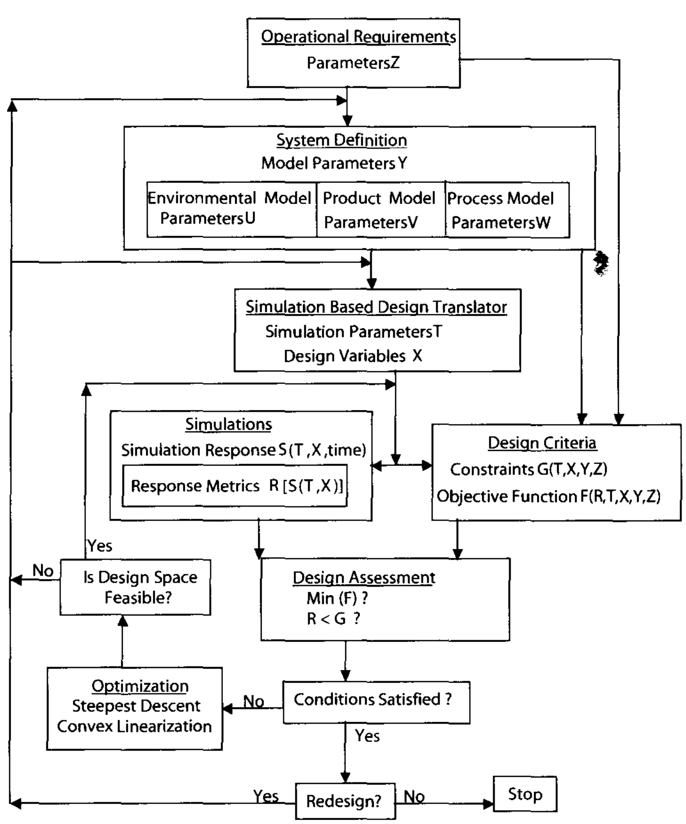

Figure 18.67 A Generic Design Framework (120)

The system definition module [Y(U,V,W)] is used to build an environmental model [U], a product model [V] and a process model [W]. The system definition module receives operational requirements [Z] such as owner's requirements. These operational parameters are presumed fixed throughout the design.

They of course can eventually be changed if no acceptable design is established, but presumably any design would have operational parameters, which would not be sacrificed. The environmental model [U] includes the still water and wave loading conditions and the product model [V] contains the production information, for example. The process model [W] is built to consider or define the fabrication sequence. A translator (simulation based design translator) assigns some [Y] model parameters to the simulation parameters [T] and design variables [X].

These parameters are selected based on the available simulation tools [S] that require specific data ([T],[X] and time).

The simulation module [SeT, X, time)] is used to produce simulation responses such as *Response Metrics* [R[S(T, X)]]. The time is needed to consider the dynamic effects and actual dynamic load conditions [U].

The optimum design module includes the Design Criteria, the Design Assessment and the Optimization components. The design criteria module provides constraints [G(T, X, Y, Z)] and objective functions [F(R, T, X, Y, Z)]. These are used to assess the design through the Design Assessment component of the module (for example R~G). The constraints are obtained by considering not only the simulation parameters [T] and the design variables [X] but also the operational requirements [Z] and the system definition parameter [Y]. Also, the objective function [F] is calculated using the response rnetrics [R], the operational requirements [Z], the system definition parameter [Y] as well as the design variables [X] and simulation parameters [T].

Based on the results of the Design Assessment (Min(F) and R~G) several strategies for the design procedure (iterations) can be followed:

- if the object function does not reach its minimum value or the response metrics do not satisfy the constraints, an optimization algorithm (steepest descent, dual approach and convex linearization, evolutionary strategies, etc.) is adopted to find a new set of design variables. Standard algorithms are presented in (113,114,123):
  - if the optimizerfails to find an improved solution (unfeasible design space), it is required to change the simulation parameter values [T] and/or design variables selection [X] or even to modify the Model Parameters [Y].

- otherwise, the design space is feasible, and a change of design variable values [Xl is performed based on the optimizer solution (in other words a new iteration).

• if the object function reaches its minimum value and the response metrics satisfy the constraints, two alternatives are examined:

- change the operational requirements parameters [Z], repeat the previous procedure and to compare with other alternative designs, or
- end the design procedure.

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Chapter 19

Reliability-based Structural Design

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19.1 INTRODUCTION

19.1.1 Structural Design

The main objective of structural design is to insure safety, functional, and performance requirements of an engineering system for target reliability levels and a.specified time period. As this must be accomplished under conditions of uncertainty, probabilistic analyses are needed in the development of such reliability-based design of panels and fatigue details of ship structures. The reliability-based structural design formats are more flexible and rational than their counterparts, the working stress formats, because they provide consistent levels of safety over various types of structural components. Such a design procedure takes into account more information than the deterministic methods in the design of ship structural components. This information includes uncertainties in the strength of various ship structural elements, in loads, and modeling errors in analysis procedures.

Uncertainties in an engineering system can be mainly attributed to ambiguity and vagueness is defining the variables and parameters of the system and their relations. The ambiguity component is generally due to noncognitive sources (1). These noncognitive sources include:

- model uncertainties, which result from simplifying assumptions in analytical and prediction models,
- statistical uncertainties of the parameters and variables, and
- physical randomness.

The vagueness sources, on the other hand, include:

- human factors,
- the definition of certain variables or parameters, for example, structural performance (failure or survival), quality, and skill and experience of construction workers and engineers, and
- defining the interrelationships among the parameters of the problem.

Reliability and risk considerations are vital to the analysis and design of an engineering system. The reliability of the system can be stated in reference to some performance criteria. The need for reliability analysis stems from the fact that there is a presence of uncertainty in the definition, understanding, modeling, and behavior prediction of the model (models) that describes the system. The objective of the analysis is the assurance of some level of reliability. Because there are numerous sources of uncertainties associated with an engineered system, the absolute safety cannot be guaranteed. However, a likelihood of unacceptable performance can be limited to a reasonable level. Estimation of this likelihood, even when used to compare various design alternatives, is an important task for a practicing engineer.

The design, analysis, and planning of any engineering system require the basic concept that the supply should be greater or at least satisfy the demand. Depending on the type of problem at hand, different terminology is used to describe this concept. For example, in structural engineering the supply can be expressed in terms of the resistance (strength) of the system (or component, that is, a beam), and the demand can be expressed in terms of the applied loads, load combinations, and their effects (that is, dead and live loads). In hydrology engineering, the height and location of a dam to be built across a river may represent the capacity (supply). On the other hand, annual rainfall, catchments areas, vegetation, and other rivers or streams flowing into the river may represent demand (2).

The notion here is no matter how the supply and demand are presented or modeled, a variety of engineering problems must satisfy this concept. Ship structural design must provide for adequate safety and proper functioning of a structural element regardless of what concept of design is used. Structural elements must have adequate strength to permit proper functioning during their intended service life.

19.1.2 Need for Reliability-based Ship Design

In recent years, reliability-based design and analysis for ship structures has received increasing interest. Numerous efforts have been made to implement the theory or at least develop the basis for the analyses of some aspects of design stages. As it is common with other industries and classification societies, we see that reliability and risk methodologies are at least being considered. Examples of such efforts are the recent works of the U.S. Navy (USN), the American Bureau of Shipping (ABS), and others to develop reliability-based standards and guidelines for such design approaches.

Such design approaches take into account more information than deterministic methods in the design of ship structural components. This information includes uncertainties in the strength of various structural elements, in loads and load combinations, and modeling errors in analysis procedures. Probability-based design formats are more flexible and rational than their counterparts the working stress formats because they provide consistent le~ls of safety over various types of structures. In probability-based limit-state design, probabilistic methods are used to guide the selection of strength (resistance) factors and load factors, which account for the variability in the individual resistance and loads and give the desired overall level of reliability. The load and resistance factors (or called partial safety factors) are different for each type of load and resistance. Generally, the higher the uncertainty associated with a load, the higher the corresponding load factor; and the higher the uncertainty associated with strength, the lower the corresponding strength factor.

Ship designers can use the load and resistance factors in limit-state equations to account for uncertainties that might not be considered properly by deterministic methods without explicitly performing probabilistic analysis. For designing code provisions, the most common format is the use of load amplification factors and resistance reduction factors (partial safety factors), as represented by

$$\phi R \geq \sum_{i=1}^{n} \gamma_i L_i \qquad [1]$$

where:

ϕ = the resistance R reduction factor
γ_i = the partial load amplification factor
L_i = the load effect

In fact, the American Institute of Steel Construction (AISC) and other classification societies in this area have implemented this format. Also, a recommendation for the use of this format is given by the National Institute of Standards and Technology (3). TheAISC (4) has introduced the Load and Resistance Factor Design (LRFD) Specifications in 1986 after the adoption of several American, Canadian, and European organizations of reliability-based design specifications. The development of the AISC LRFD code was based on a probability-based model, calibration with the 1978 AISC Allowable Stress Design (ASD) Specifications, and expert sound engineering judgment based on previous design experiences. In developing the specifications, it was necessary to change the design practice from working stress to limit stress, and from allowable stress to ultimate strength, which was reliability-based.

Currently, the American Association of State Highway and Transportation Officials (AASHTO) Specifications have been revised to an LRFD format. The National Cooperative Highway Research Program (NCHRP) has published the third Draft of LRFD Specifications and Commentary in 1992 entitled *Development of Comprehensive Bridge Specifications and Commentary.* The AASHTO LRFD (1) code closely follows much of the AISC code. Many of the individuals that were instrumental in the development of the AISC LRFD code were involved with the AASHTO effort.

Other marine and offshore classification societies that are in the process of revising, or have already revised and updated their codes to LRFD format include the U.S. Navy (USN), the American Bureau of Shipping (ABS), the American Petroleum Institute (API), the Association of American Railroads (AAR), Lloyd's Register (LR), and Det Norske Veritas (DnV).

As we will see in the subsequent sections, the First-Order Reliability Method (FORM) can be used to evaluate the partial safety factors ϕ and γ_i (appearing in equation 1) for a specified target levels of reliability. This method was used to determine the partial safety factors associated with the recommended strength models for ship structural components as demonstrated in this chapter.

19.2 SHIP STRUCTURAL COMPONENTS

19.2.1 Hull Girder

One of the fundamental concepts of engineering is that of a system, which can be anything from a simple beam or detail to complicated multilevel subsystems. A ship obviously falls into the category of a relatively large and complex system. The ship consists of several subsystems, which are essential to the integrity of the whole system. Examples of these subsystems are the hull girders, unstiffened and stiffened panels, and structural fatigue details. Probably the most essential part of a ship design is the hull girder system or model. Environmental loads, either static or dynamic, that are due to sea environment and ship's motion are functions of the hull shape. However, much of these loads are relatively independent of the substructures (subsystems) such as unstiffened and stiffened plate elements, that is, they are not affected by the structural layout and shape or by scantlings. Therefore, the design of the hull girder is the first step toward designing the other substructures of a ship because much of the overall load effects on the hull girder can be used for designing these substructures or subsystems.

In a large structure, such as a hull girder, both the loading and the response are extremely complex, and therefore, the response analysis must be performed in two stages (5), 1) an analysis of the overall structure, and 2) a separate and more detail analyses of different substructures.

Many of the load effects from the overall analysis constitute the loads and boundary conditions at the substructure level. The overall structure of a ship is essentially a floating beam (box girder) that internally stiffened and subdivided, and in which the decks and bottom structure are flanges and the side shell and any longitudinal bulkheads are the webs. External forces and moments on a hull gifer are those forces or moments that are applied on a beam such as vertical shear force (fy), longitudinal bending moment in the ship's vertical and horizontal planes (My and M_z), and longitudinal twisting moment Mx' The most significant of all these forces and moments is the vertical bending moment of the hull girder about the z-axis as shown in Figure 19.1. This load affect is due primarily to the unequal distribution of the weight (W) of the ship and buoyancy (B_F) along the length of the ship due to waves as shown in Figure 19.2. F~r many ships, the maximum value of the horizontal moment My is much smaller than the vertical moment M_z, typically 19% or less (5).

The vertical bending moment varies along the length of the ship. It can take values from zero at the ends to a maximum at or near the midlength of the ship. This maximum value of the vertical moment for hull girder is the single most important load effect in the analysis and design of ship structures. Hull girder bending can be caused by either hogging or sagging depending on the curvature due waves as shown in Figure 19.2. The hull girder analysis and design assumes that the hull girder satisfies simple beam theory that implies the following assumptions (5):

- Plane cross sections remain plane,
- The beam is essentially prismatic,

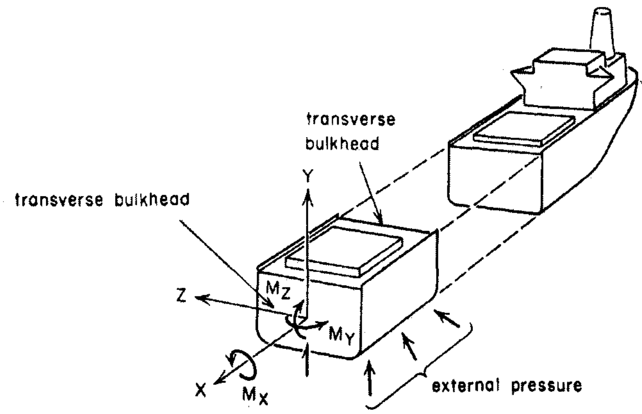

Figure 19.1 Hull Girder Model of a Ship (5)

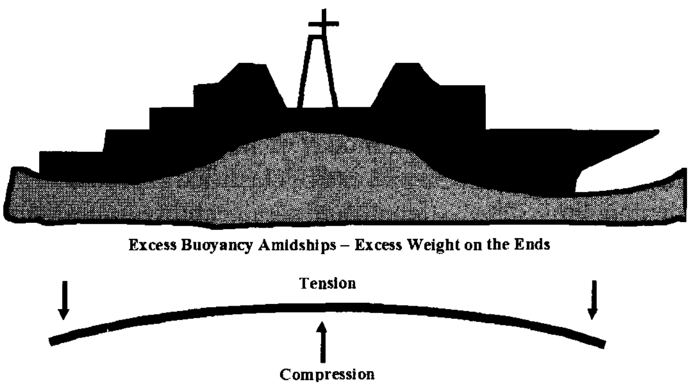

Figure 19.2A Hogging Condition of a Ship Due to Sea Waves

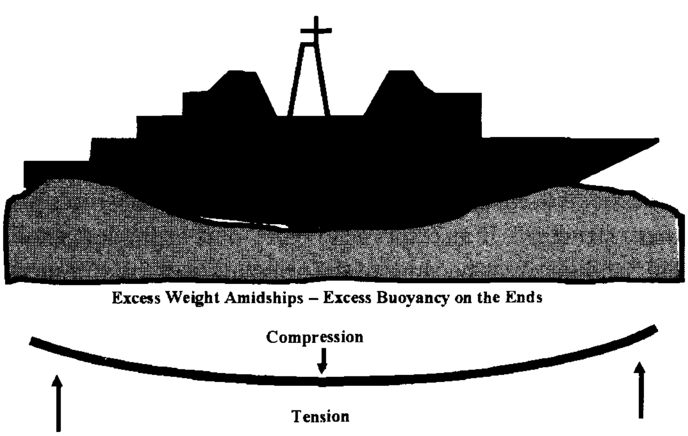

Figure 19.2B Sagging Condition of a Ship Due to Sea Waves

- Other modes of response to the loads do not affect hull girder bending and may treated separately, and
- The material is homogeneous and elastic.

19.2.2 Ship Steel Panels

The structural components that make up the hull girder are the panels or plate elements. Ship panels, in general, can be divided into three distinct categories, 1) unstiffened, 2) stiffened, and 3) gross panels or grillages (Figures 19.3 and 19.4).

These panels (or called plates) are very important components in ship and offshore structures, and, therefore, they should be designed for a set of failure modes that govern their strength.

They form the backbone of most ship's structure, and they are by far the most commonly used element in a ship. They can be found in bottom structures, decks, side shell, and superstructures. The modes of failure, which govern the strength of these panels, can be classified to produce two distinct limit states, strength and serviceability limit states. Strength limit states are based on safety consideration or ultimate load-carrying capacity of a panel and they include plastic strengths, buckling, and permanent deformation. Serviceability limit states, on the other hand, refer to the performance of a panel under normal service loads and are concerned with the uses of unstiffened and stiffened plates, and gross panels. They include such terms as excessive deflections and first yield. Also, strength limit states require the definition of the lifetime extreme loads and their combinations, whereas serviceability limit states require annual-extreme loads and their combinations.

The primary purpose of a panel is to absorb out of plane (or lateral) loads and distribute those loads to the ship's primary structure. It also serves to carry part of the lon~tudinal bending stress because of the orientation of the stiffeners. The amount of in-plane compression or tension experienced depends primarily on the location of the panel within the ship. Deck panels tend to experience large in-plane compression and small lateral pressures, while bottom panels can be exposed to large in-plane tension and compression with a significant amount of lateral pressures.

The main type of framing system found in ships nowadays is a longitudinal one, which has stiffeners running in two orthogonal directions (Figure 19.3). Deck and bottom structures panels are reinforced mainly in the longitudinal direction with widely spaced heavier transverse stiffeners. The main purpose of the transverse stiffeners is to provide resistance to the loads induced on bottom and side shell by water pressure (6). The types of stiffeners used in the longitudinal direction are the T-beams, angles, bulbs, and flat bars, while the transverse stiffeners are typically T-beam sections. This type of structural configuration is commonly called gross stiffened panel or grillage (6). Besides their use in ship structures, these gross stiffened panels are also widely used in land-based structures such as box and plate girders.

The overall collapse of a gross panel involves global deflection of both longitudinal and transverse stiffeners. However, except for lightly stiffened panels found in superstructures, this type of failure rarely occurs because most ship structures are designed to prevent the overall mode of collapse (7,8). In most cases local plate buckling is the weakest failure mode. Global failure of a stiffened panel can be partially controlled by careful design of strength of the plate elements (unstiffened panels) between stiffeners. The most common mode of failure of the whole panel

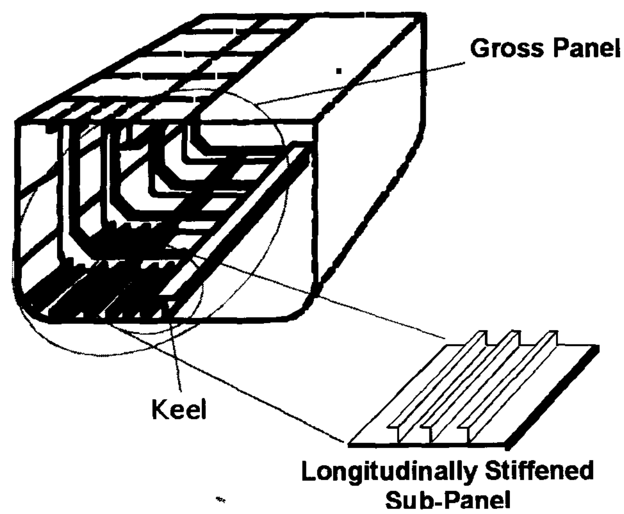

Figure 19.3 Portion of the Hull Girder Showing the Gross Panel and a Longitudinally Stiffened Subpanel (5)

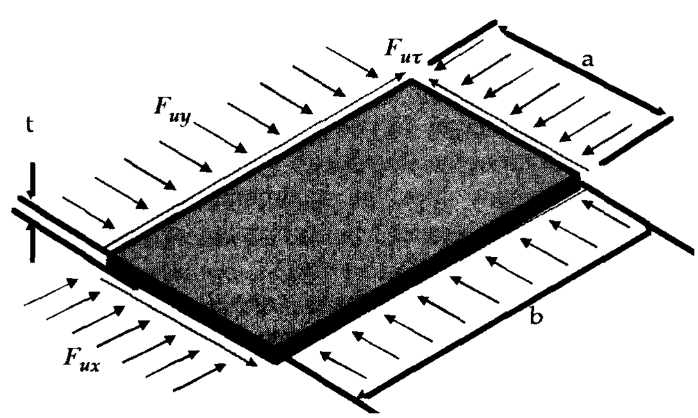

Figure 19.4 Unstiffened Panel Subjected to In-Plane Stresses

involves the collapse of the longitudinally stiffened subpanel. Choosing the size of the transverse stiffeners so that they provide sufficient flexural rigidity to enforce nodes at the location ofthe transverse stiffeners can prevent the collapse of longitudinally stiffened subpanel. If the transverse stiffeners act as nodes, then the collapse of the stiffened panel is controlled by the strength of the longitudinally stiffened subpanel.

A typical longitudinal stiffened subpanel, as shown in Figure 19.3, is bounded on each end by a transverse structure, which has significantly greater stiffness in the plane of the lateral load. The sides of the panel are defined by the presence of a large structural member that has greater stiffness in bending and much greater stiffness in axial loading. Structural members such as keels, bottom girders, longitudinal bulkheads, deck girders, etc., can act as the side boundaries of the panel. When the panel is located to be in a position to experience large in-plane compression, the boundary conditions for the ends are taken as simply supported. The boundary conditions along the sides also can be considered simply supported.

In ship structures, there are three primary types of load effects that can influence the strength of a plate-stiffener panel (negative bending moment, positive bending moment, and in-plane compression or tension). Negative bending loads are the lateral loads due to lateral pressure. They cause the plate to be in tension and the stiffener flange in compression. Positive bending loads are those loads that put the plating in compression and the stiffener flange in tension. The third type of loading is the uniform in-plane compression. This type of loading arises from the hull girder bending, and will be considered positive when the panel is in compression. The three types of loading can act individually or in combination with one another. t

To evaluate the strength of a stiffened or gross panel element it is necessary to review various strength prediction models and to study their applicability and limitations for different loading conditions acting on the element. Although stiffened plate strength has been studied for many years, several advanced strength models have been developed during the last few decades. These advanced models take into account the effects of initial distortion; weld induced residual stresses, and various parameters concerning strength prediction. Some of these models are empirical in nature but they are highly representative of real world scenario because they were developed on the bases of experimental data. An exact stiffened panel-strength prediction can only be achieved by a method of analysis, either numerical or experimental, in which all the characteristics of the panel and the loading variables are presented and are properly accounted for in the method.

19.3 RELIABILITY, RISK, SAFETY, AND PERFORMANCE

Reliability of a system can be defined as its ability to fulfill its design functions for a specified time period. This ability is commonly measured using probabilities. Reliability is, therefore, the occurrence probability of the complementary event to failure resulting into

$$\text{Reliability} = 1 - \text{Failure Probability} \qquad [2]$$

Based on this definition, reliability is one of the components of risk. The concept of risk is used to assess and evaluate uncertainties associated with an event. Risk can be defined as the potential of losses as a result of a system failure, and can be measured as a pair of the probability of occurrence of an event, and the outcomes or consequences associated with the event's occurrence. This pairing can be represented by the following equation:

$$\text{Risk} \equiv \left[(p_1, c_1), (p_2, c_2), \ldots, (p_x, c_x)\right] \qquad [3]$$

In this equation p_x is the occurrence probability of event x, and c_x is the occurrence consequences or outcomes of the event. Risk is commonly evaluated as the product of likelihood of occurrence and the impact of an accident:

$$\text{RISK}\left(\frac{\text{Consequence}}{\text{Time}}\right) = \text{LIKELIHOOD}\left(\frac{\text{Event}}{\text{Time}}\right) \times \text{IMPACT}\left(\frac{\text{Consequence}}{\text{Event}}\right) \qquad [4]$$

In equation 4, the likelihood can also be expressed as a probability. A plot of occurrence probabilities that can be annual and consequences is called the Farmer curve (9).

The risk assessmenf'process answers three questions including,

1. what can go wrong,
2. what is the likelihood that it will go wrong, and
3. what are the consequences if it does go wrong?

In order to perform risk assessment several methods have been created including: Preliminary Hazard Analysis (PrHA), HAZOP, Failure Modes and Effects Analysis (FMEA), Failure Modes Effects, and Criticality Analysis (FMECA), Fault Tree Analysis (FTA), and Event Tree Analysis (ETA). Each of these methods of risk assessment is suitable in certain stages of the system life cycle. The characteristics of these methods are shown in Table 19.r. In-depth description of risk management, methods for reliability and consequence analysis and assessment are described in references 10 and 11.

Safety can be defined as the judgment of risk accept-

TABLE 19.1 Risk Assessment Methods (9)

Safety/Review Audit	Identify equipment conditions or operating procedures that could lead to a casualty or result in property damage or environmental impacts.
Checklist	Ensure that organizations are complying with standard practices.
What-If	Identify hazards, hazardous situations, or specific accident events that could result in undesirable consequences.
Hazard and Operability Study (HAZOP)	Identify system deviations and their causes that can lead to undesirable consequences. Determine recommended actions to reduce the frequency and/or consequences of the deviations.
Failure Modes and Effects Analysis (FMEA)	Identifies the components (equipment) failure modes and the impacts on the surrounding components and the system.
Failure Modes Effects, and Criticality Analysis (FMECA)	Identifies the components (equipment) failure modes and the impacts on the surrounding components and the system, and criticality of failures.
Fault Tree Analysis (FTA)	Identify combinations of equipment failures and human errors that can result in an accident.
Event Tree Analysis (ETA)	Identify various sequences of events, both failures and successes that can lead to an accident.
Preliminary Hazard Analysis (PrHA)	Identify and prioritize hazards leading to undesirable consequences early in the life of a system. Determine recommended actions to reduce the frequency and/or consequences of prioritized hazards.
Consequence Assessment and Cause Consequence Diagrams	Assess consequences and scenarios leading to them.

ability for the system making it a component of risk management.

After performing risk and safety analysis, syst~ improvement in terms of risk can be achieved by one or more of the following cases:

- consequence reduction in magnitude or uncertainty,
- failure-probability reduction in magnitude or uncertainty, and
- reexamination of acceptable risk.

It is common in engineering that attention is given to failure-probability reduction in magnitude or uncertainty because it offers more system variables that can be controlled by analysts than the other two cases. As a result, it is common to perform reliability-based design of systems. However, the other two cases should be examined for possible solution since they might offer some innovative system improvement options.

The performance of a systems can be defined by a set of requirements stated in terms of tests and measurements of how well the system serves various or intended functions. Reliability and risk measures can be considered as performance measures.

19.3.1 Measures and Assessment of Reliability and Risk

Traditionally, the reliability of engineering systems has been achieved through the use of factors of safety (PS) in the so-called working stress (or allowable stress design, ASD) formats. The safety factor, whose value provides a quantitative measure of reliability or safety, differs from one design specification to another and from one type of structure (that is, beam, column, plate, etc.) to another. It reflects the degree of reliability and risk associated with that particular component. Por example, this value can range from 2 to 4 for land-based structural systems, and from 3 to 5 or even 6 in geotechnical engineering applications, depending on the type of structural system or component under consideration.

This measure of reliability or safety was intended to reflect the probability of failure of the system and the risk associated with it.

The traditional approach is difficult to quantify and lacks the logical basis for addressing uncertainties. Therefore, the level of reliability or safety cannot be evaluated quantitatively. Also, for new systems in which there is no prior basis for calibration, the assurance of performance can be a very difficult task.

In reliability-based design and analysis approaches, the measure of reliability or safety is accomplished through the use of reliability (safety) index ~. In this respect, the role of ~ is to reflect the reliability level used in the analysis. In practical structural analysis, ~ can be computed using structural reliability theory and knowledge of the first and second moments statistical characteristics (that is, mean and *COV)* for both the strength and load variables. Sometimes in more rigorous analyses, the distribution types of these variables are needed. Also, a definition of a performance (or criterion) function is required. For two variables and linear performance function, the reliability index P can be defined as the shortest distance from the origin to the failure line as shown in Figure 19.5. Mathematically, it can be expressed as

$$\beta = \frac{\mu_R - \mu_L}{\sqrt{\sigma_R^2 + \sigma_L^2}} \qquad [5]$$

where

μ_R = mean value of strength R
μ_L = mean value of the load effect L
σ_R = standard deviation of strength R
σ_R = standard deviation of the load effect L

The reliability index according to this definition is commonly referred to as the Hasofer-and-Lind index (12).

A distinction should be made between the reliability index β and target reliability index β_0. Target reliability index values are used by the classification societies to set the standards for code provisions to meet the design requirements of various structural components (or systems). These values can vary depending on the type of structural component being analyzed and the risk associated with its design. On the other hand, computed reliability index values are used to check the adequacy and performances of existing structures. In this approach, the computed value of the safety or reliability index is compared with the target reliability index.

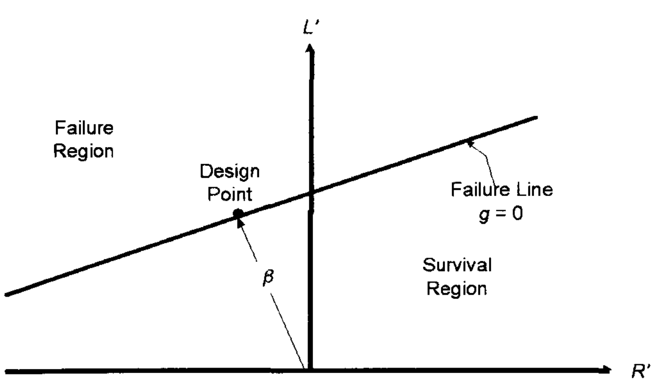

Figure 19.5 Performance Space in Reduced Coordinates

If, for example, the computed value of the reliability index ~ is greater than the target reliability index ~o' then the structural component under study is adequate to withstand the prescribed load effect.

Table 19.II and III provide examples target reliability levels used in the industry, while Table 19.IV gives target reliability index values for ship structural components.

19.3.2 Selection of Target Reliability levels

As was alluded to earlier, target reliability levels, ~os, are used by the classification societies to set the standards for code provisions to meet the intended design requirements of various structural components (or systems).

These target levels can vary depending on the type of structural component being analyzed and the risk associated with its design. Reliability-based design guidelines and rules for ship structures require establishing these target levels for the design and analyses of the structural components. The selected reliability level determines the proba-

TABLE 19.II Target Reliability Levels (13)

Structural Type	*Target Reliability Level* (β_0)
Metal structures for buildings (dead, live, and snow loads)	3
Metal structures for buildings (dead, live, and wind loads)	2.5
Metal structures for buildings (dead, live, and snow, and earthquake loads)	1.75
Metal connections for buildings (dead, live, and snow loads)	4 to 4.5
Reinforced concrete for buildings (dead, live, and snow loads)	
ductile failure	3
brittle failure	3.5

TABLE 19.III Target Reliability Levels Used by Ellingwood and Galambos (14)

Member, Limit State	*Target Reliability Level* (β_0)
Structural Steel	
Tension member, yield	3.0
Beams in flexure	3.0
Column, intermediate slenderness	3.5
Reinforced Concrete	
Beam in flexure	3.0
Beam in shear	3.0
Tied column, compressive failure	3.5
Masonry, unreinforced	
Wall in compression, uninspected	5.0
Wall in compression, uninspected	7.5

TABLE 19.IV Recommended Target Safety Indices Relative to Service Life of Ships (13)

	Tanker β_0	*Cruiser* β_0
Hull girder collapse	4	5
Hull girder initial yield	4.5	5.5
Unstiffened panel	3	3.5
Stiffened panel	3.5	4
Fatigue		
Category 1 (Not Serious)	2.0	2.5
Category 2 (Serious)	2.5	3.0
Category 3 (Very Serious)	3.0	3.5

bility of failure of the ship structural component being analyzed. The following three methods can be used to select a target reliability value, 1) agreeing upon a reasonable value in cases of novel structures without prior history, 2) calibrating reliability levels implied in currently used successful design codes, and 3) choosing target reliability level that minimizes total expected costs over the service life of the structure for dealing with design for which failures result in only economic losses and consequences.

Since the development herein is limited to ship structural components that are not novel structures, the first method is excluded. The modes of failure for ship structural components have serious consequences such as the entire loss of the ship, loss oflives, and environmental damages (water pollution in case oftankers or chemical carriers). Accordingly, the second method seems to be the proper one to be adopted for selecting target reliability levels since there are a lot of data available from currently used design codes that resulted in safe structures with adequate reliability.

19.4 RELIABILITY-BASED STRUCTURAL DESIGN APPROACHES

The reliability-based design of any structural system requires the consideration of the following three components 1) loads, 2) structural strength, and 3) methods of reliability analysis.

These three components can be presented in the form of several blocks for each to show their logical sequence and interaction. The reliability-based design procedure also requires the probabilistic characteristics of the strength and load basic random variables as well as defining performance functions that correspond to limit states for significant failure modes. There are two primary approaches for reliability-based design (9), 1) direct reliability-based design, and 2) load and resistance factor design (LRFD).

The direct reliability-based design approach can include both Level 2 and/or Level 3 reliability methods. Level 2 reliability methods are based on the moments (mean and variance) of random variables and sometimes with a linear approximation of nonlinear limit states, whereas, Level 3 reliability methods use the complete probabilistic characteristics of the random variables. In some cases, Level 3 reliability analysis is not possible because oflack of complete information on the f~ll probabilistic characteristics of the random variables. Also, computational difficulty in Level 3 methods sometimes discourages their uses. The LRFD approach is called a Level 1 reliability method. Levell reliability methods utilize partial safety factors (PSF) that are reliability based; but the methods do not require explicit use of the probabilistic description of the variables.

The many advantages and benefits of using reliability-based design methods include the following:

- they provide the means for the management of uncertainty in loading, strength, and degradation mechanisms,
- they provide consistency in reliability,
- they result in efficient and possibly economical use of materials,
- they provide compatibility and reliability consistency across materials, such as, steel grades, aluminum and composites,

- they allow for future changes as a result of gained information in prediction models, and material and load characterization,
- they provide directional cosines and sensitivity factors that can be used for defining future research and development needs,
- they allow for performing time-dependent reliability analysis that can form the bases for life expectancy assessment, life extension, and development of inspection and maintenance strategies,
- they are consistent with other industries, AISC, ASHTO, ACI, API, ASME, ... , etc, and
- they allow for performing system reliability analysis.

19.4.1 Fundamentals of Reliability-based Design

The design of any structural system or element must provide for adequate safety and proper functioning of that system or element regardless of what philosophy of design is used. The structural systems or elements must have adequate strength to permit proper functioning during their intended service life. For example, the performance of a ship hull girder as presented in the chapter is defined by a set of requirements stated in terms of tests and measurements of how well the hull girder serves various or intended functions over its service life. Reliability and risk measures can be considered as performance measures, specified as target reliability levels (or target reliability indices, ~os). The selected reliability levels of a particular structural element reflect the probability of failure of that element. These levels can be set based on implied levels in the currently used design practice with some calibration, or based on cost benefit analysis.

For ship structures, the reliability-based design approaches for a system start with the definition of a mis;on and an environment for a ship. Then, the general dimensions and arrangements, structural member sizes, scantlings, and details need to be assumed. The weight of the structure can then be estimated to ensure its conformance to a specified limit. Using an assumed operational-sea profile, the analysis of the ship produces a stochastic still water and wave-induced responses. The resulting responses can be adjusted using modeling uncertainty estimates that are based on any available results of full-scale or large-scale testing.

The reliability-based design procedure also requires defining performance functions that correspond to limit states for significant failure modes. In general, the problem can be considered as one of supply and demand. Failure of a structural element occurs when the supply (that is, strength of the element) is less than the demand (that is, loading on the element). On the other hand, the reliability of this element is achieved when the supply is greater than the demand.

19.4.1.1 Reliability of structural components

The reliability of a structural component constitutes the basis for performing system reliability of larger structure. In general, a component can fail in one of several failure modes. The treatment of multiple failure modes requires modeling the component behavior as a system. In addition, the system can be defined as a collection or an assemblage of several components that serves some function or purpose (15). A multi-component system can fail in several failure modes. Once the reliability or probability of failures for all of the components that make up the whole systems is evaluated, system reliability can be performed on the overall system. The theory of system reliability is beyond the scope of this chapter. Numerous excellent books and references have been written for the subject, and the reader is encouraged to read references (1,9,15,29,31).

The reliability of a structural component can be defined as the probability that the component meets some specified demands. For example, the reliability of a structural component such as a beam can be defined as the probability that structural strength of the beam (that is, ultimate moment capacity) exceeds the applied load (that is, moment due to the total combined loads). The first step in evaluating the reliability or probability of failure of a structural component is to decide on specific performance function g and the relevant load and resistance variables. The generalized form of the performance function can be expressed as

$$g = R - L \qquad [6]$$

or

$$g = f(X_1, X_2, \ldots X_n) \qquad [7]$$

where

g = the performance function
$X_1, X_2, \ldots, X_n$ = n basic random variables for R and L
$f(.)$ = a function that gives the relationship between R and L and the basic random variables.

The failure in this case is defined in the region where g is less than zero (see Figure 19.6) or R is less than L, that is

$$g = < 0.0 \text{ or } R < L \qquad [8]$$

whereas the reliability is defined in the region where g is greater than zero (Figure 19.6) or R is greater than L, that is

$$g = > 0.0 \text{ or } R > L \qquad [9]$$

The limit state is defined when g = 0.

Due to the variability in both strength and loads, there is always a probability of failure that can be defined as

$$P_f = P(g < 0.0) = P(R < L) \qquad [10]$$

The reliability of a structural component can be defined as the probability that the component meets some specified demands for a specified time frame.

Mathematically, it can be given by the following expression:

$$R_c = P(g > 0.0) = P(R > L) \qquad [11]$$

where P_f = probability of the system or component and R_c = reliability of the component. According to probability theory, since failure and non-failure (or success) constitute two complementary events, therefore,

$$P_f = 1 - R_c \qquad [12]$$

For the general case, where the basic random variables can be correlated, the probability of failure for the component can be determined by solving the following integral:

$$P_f = \int_{\text{over } g \le 0} \cdots \int f_{\underline{X}}\left(x_1, x_2, \cdots x_n\right) dx_1 dx_2 \cdots dx_n \qquad [13]$$

where fx is the joint probability density function (PDF) of the random vector $\underline{X}$ = [X r X_2, ... , Xnl; and the integration is performed over the region where g = f(.) < 0. The computation of Pf by equation 13 is called the *full distributional approach* and can be considered the fundamental equation of reliability analysis (29). In general, the determination of the probability of failure by evaluating the integral of equation 13 can be a difficult task. In practice, the joint probability density function fx is hard to obtain. Even, ifthe PDF is obtainable, evaluation of the integral of equation 13 requires numerical methods. In practice, there are alternative methods for evaluating the above-mentioned integral through the use of analytical approximation procedure~ such as the First-Order Reliability Method (FORM), wlfich is the focus of our discussion in the next section.

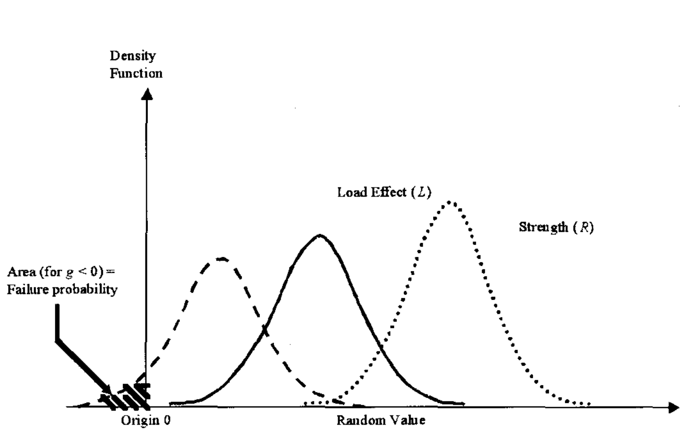

Figure 19.6 Frequency Distribution of Strength *R* and Load *L*

19.4.1.2 First-order reliability method

The First-Order Reliability Method (FORM) is a convenient tool to assess the reliability of a ship structural element. It also provides a means for calculating the partial safety factors ⟐ and Yi that appear in the LRFD design formula of equation 1 for a specified target reliability level ~o. The simplicity of the first-order reliability method stems from the fact that this method, beside the requirement that the distribution types must be known, requires only the first and second moments; namely the mean values and the standard deviations of the relevant random variables. Knowledge of the joint probability density function (PDF) of the design basic variables is not needed as in the case of the direct integration method for calculating the reliability index ~. Even if the joint PDF of the basic random variables is known, the computation of ~ by the direct integration method as given by equation 13 can be a very difficult task.

The development of FORM over the years resulted in many variations of the method. These variations (29) include such methods as the first-order second moment (FOSM) and the advanced first-order second moment (AFOSM). Both of these methods use the information on first and second moments of the random variables, namely, the mean and standard deviation (or the coefficient of variation, *COV)* of a random variable. However, the FOSM method ignores the distribution types of the random variables, while AFOSM takes these distributions into account. Clearly, the AFOSM method as the name implies produces more accurate results than FOSM. Nevertheless, FOSM can be used in many situations of preliminary design or analysis stages of a structural component, where the strength and load variables are assumed to follow a normal distribution and the performance function is linear. In these cases, the results of the two methods are essentially the same.

The importance of FORM is that it can be used in structural analysis to compute the reliability index ~, and also to determine the partial safety factors (PSF's) in the development of various design codes. The reliability index was defined earlier as shortest distance from the origin to the failure line as shown in Figure 19.5. For normal distributions of the strength and load variables, and linear performance function, ~ can be computed using equation 5. The important relationship between the reliability index ~ and the probability of failure Pf is given by

$$P_f = 1 - \Phi(\beta) \qquad [14]$$

where $\Phi(.)$ = cumulative probability distribution function of the standard normal distribution. It is to be noted that equation 14 assumes all the random variables in the limit state equation to have normal probability distribution and the performance function is linear. However, in practice, it is common to deal with nonlinear performance functions with a relatively small level on linearity. If this is the case, then the error in estimating the probability of failure P_f is very small, and thus for all practical purposes, equation 14 can be used to evaluate P_f with sufficient accuracy (3).

The nominal values of partial safety factors (PSFs) according to the linear performance function given by equations 6 and 7, and for normal distributions of the strength and load variables can be calculated using the following two expressions as suggested by Halder and Mahadevan (16):

For single load case:

$$\phi = \frac{1 - \varepsilon\beta\delta_R}{1 - S_R\delta_R} \quad [15]$$

$$\gamma_L = \frac{1 + \varepsilon\beta\delta_L}{1 + S_L\delta_L} \quad [16]$$

where

$$\varepsilon = \frac{\sqrt{\sigma_R^2 + \sigma_L^2}}{\sigma_R + \sigma_L} \quad [17]$$

and in which, σ_R = standard deviation of strength R, σ_L = standard deviation of the load effect L, δ_R = coefficient of variation (COV) of the strength R, δ_L = COV of the load effect L, and S_R and S_L are parameters used by some classification societies and the industry to approximate the nominal values of the strength and the load effect, respectively. Typical values for S_R and S_L range from 1 to 3.

For multiple load case:
The nominal reduction factor ϕ of strength can still be computed from equation 15. However, the nominal load factors γ_is for the ith load effect become (22)

$$\phi = \frac{1 - \varepsilon\beta\delta_R}{1 - S_R\delta_R} \quad [18]$$

where

$$\phi = \frac{1 - \varepsilon\beta\delta_R}{1 - S_R\delta_R} \quad [19]$$

and in which, $\sigma_{L_1}^2, \sigma_{L_2}^2, \cdots, \sigma_{L_{n1}}^2$ = standard deviations of the load effects ($L_1, L_2, \ldots, L_n$) and δ_{L_i} = *COV* of the load effect L_i, and S_{L_i} = parameter used to approximate the nominal value of load effect L_i.

In general, the nominal value of the strength is less than the corresponding mean value, and the nominal value of the load effect is larger than its mean value. For example, if both S_R and S_L equal to 2, the nominal value of R would be 2 standard deviations below the mean, and the nominal value for L would be 2 standard deviations above its mean value. If S_R and S_L have zero values, then equations 15 and 16 essentially result into the mean values of the partial safety factors $\bar{\phi}$ and $\bar{\gamma}_L$, respectively. The nominal values of partial safety factors can be used in LRFD design format of the type

$$\phi R_n \geq \gamma_1 L_1 + \gamma_2 L_2 + \ldots \gamma_n L_n \quad [20]$$

For purposes of design, this relationship needs to be satisfied.

It is to be noted that equations 15 and 16 apply only for linear performance function with two variables (strength and one load effect) having normal distributions, while equation 18 applies for multiple linear case. For a general case of nonlinear function with multiple random variables having different distribution types (that is, lognormal, Type I, etc.), an advanced version of FORM should be used. Detailed algorithms of advanced FORM version as well as procedures for calculating and calibrating the partial safety factors using FORM can be found in Appendix A. It is to be noted that the version of FORM given in the appendix is the advanced first-order second moment (AFOSM). This version of FORM applies for a general case of nonlinear performance function and for any distribution type of the random variables.

EXAMPLE 19.1

Given:
A tension member in a truss has an ultimate strength T with a mean value of 623 kN and standard deviation of 53 kN. The tension load L applied to the member has a mean value of 400 kN kips and standard deviation of 111 kN. If normal distributions are assumed for T and L, what is the reliability index for this member? What is its failure probability?

Solution:
The following parameters are given:

$$\mu_T = 53 \text{ kN}$$
$$\mu_L = 111 \text{ kN}$$
$$\sigma_T = 623 \text{ kN}$$
$$\sigma_L = 400 \text{ kN}$$

Using equation 5, therefore,

$$\beta = \frac{623 - 400}{\sqrt{(53)^2 + (111)^2}} = 1.81$$

The probability of failure according to equation 14 is

$$P_f = 1 - \Phi(1.81) = 1 - 0.9649 = 0.035$$

Note: $\Phi(1.81)$ can be obtained from Tables that provide values for the cumulative distribution function of standard normal.

EXAMPLE 19.2

Given:

The fully plastic flexural capacity of a beam section can be estimated as F_y Z, where F_y = yield strength of the material (steel) of the beam and Z = plastic section modulus. If the simply supported beam shown in Figure 19.7 is subjected to mean values of distributed dead and live loads: w_O and w_L, respectively; and ifZ and L are assumed to be constant, develop the nominal and mean partial safety factors for this beam and the corresponding LRFD-based design formula for a target reliability index of 3. Assume that the nominal values are one standard deviation below the mean for the strength, and one standard deviations above the corresponding mean values for both the dead and live loads. The probabilistic characteristics of the basic random variables are as provided in Table 19.V.

Solution:

For this analysis, the following linear performance function is considered:

$$g = M_R - M_D - M_L$$

The plastic moment capacity of the beam M_p can be considered the mean moment capacity, thus

$$g = ZF_y - M_D - M_L$$

$$\begin{aligned} M_R &= M_P = ZF_y \\ &= (4588 \times 10^{-6})(248 \times 10^3) \\ &= 1137.8 \text{ kN} - \text{m} \end{aligned}$$

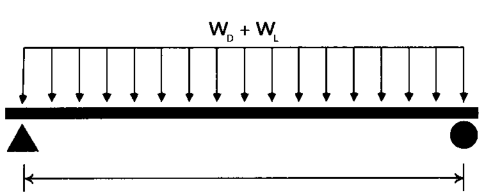

Figure 19.7 Beam Design for Example 19.2

$$\sigma_R = 1137.8\left(\frac{12.4}{248}\right) = 56.9 \text{ kN} - \text{m}$$

$$\delta_R = \frac{12.4}{248} = 0.05$$

$$\delta_D = \frac{\sigma_D}{\mu_D} = \frac{0.044}{0.315} = 0.14$$

$$\delta_L = \frac{\sigma_L}{\mu_L} = \frac{0.16}{0.438} = 0.36$$

For simply supported beam, the applied maximum moments at its mid-span can be computed as follows:

$$M_D = \frac{w_D L^2}{8} = \frac{0.315(915)^2}{8(100)} = 329.7 \text{ kN} - \text{m}$$

$$M_L = \frac{w_L L^2}{8} = \frac{0.438(915)^2}{8(100)} = 458.4 \text{ kN} - \text{m}$$

Denoting the total moment due to applied dead and live loads as M, its mean, standard deviation, and COV can be estimated:

$$\mu_M = 329.7 + 458.4 = 788.1 \text{ kN} - \text{m}$$
$$\mu_{M_D} = 329.7(0.14) = 46.16 \text{ kN} - \text{m}$$
$$\mu_{M_L} = 458.4(0.36) = 165.02 \text{ kN} - \text{m}$$

Therefore,

$$\sigma_M = \sqrt{(46.16)^2 + (165.02)^2} = 171.4 \text{kN} - \text{m}$$

$$\delta_M = \frac{171.4}{788.1} = 0.22$$

Using equations 17 and 19, the parameters ε and ε_n are calculated as follows:

$$\varepsilon = \frac{\sqrt{(56.9)^2 + (171.4)^2}}{56.9 + 171.4} = 0.79$$

TABLE 19.V Probabilistic Characteristics of Random Variables for the Beam Problem

Variable	μ	σ	*Distribution*
F_y	248 MPa	12.4 MPa	Normal
Z	4588 cm^3	n/a	n/a
L	915 cm	n/a	n/a
w_D	0.315 kN/cm	0.044 kN/cm	Normal
w_L	0.438 kN/cm	0.16 kN/cm	Normal

$$\varepsilon_n = \frac{\sqrt{(46.16.24)^2 + (165.02)^2}}{46.16 + 165.02} = 0.81$$

According to equations 15 and 18, and noting that $S_R = S_D = S_L = 1$ for both the strength and load effects, the nominal partial safety factors (PSFs) are obtained as follows:

$$\phi = \frac{1 - 0.79(3)(0.05)}{1 - (1)(0.05)} = 0.93$$

$$\gamma_D = \frac{1 + 0.79(0.81)(3)(0.14)}{1 + (1)(0.14)} = 1.11$$

$$\gamma_L = \frac{1 + 0.79(0.81)(3)(0.36)}{1 + (1)(0.36)} = 1.24$$

Thus, the LRFD-based design formula is given by

$$0.93R \geq 1.11D + 1.24L$$

The mean values of the partial safety factors can be found using equations 15 and 18, with $S_R = S_D = S_L = 0$. The results are:

$$\bar{\phi} = 0.88$$
$$\bar{\gamma}_D = 1.27$$
$$\bar{\gamma}_L = 1.69$$

EXAMPLE 19.3

Given:

Develop the mean values of partial safety factors for the simply supported beam of Example 19.2 using the probabilistic characteristics for the random variables as provided in Table 19.VI.

Solution:

In this example, we note that the distribution types of the random variables are no longer normal. We have a mixture of distributions for these variables. Therefore, the simplified methods of this section cannot apply directly even though the performance function is the same, that is

$$g = ZF_y - M_D - M_L$$

To compute the mean values of the partial safety factors, the general procedure of FORM, as outlined in Appendix A, should be utilized. The results are as follows:

$$\bar{\phi} = 0.97$$
$$\bar{\gamma}_D = 1.05$$
$$\bar{\gamma}_L = 2.63$$

TABLE 19.VI Probabilistic Characteristics of Random Variables for Example 19.3

Variable	μ	σ	*Distribution*
F_y	248 MPa	12.4 MPa	Lognormal
Z	4588 cm^3	n/a	n/a
L	915 cm	n/a	n/a
w_D	0.315 kN/cm	0.044 kN/cm	Normal
w_L	0.438 kN/cm	0.16 kN/cm	Type I

19.4.2 Direct Reliability-based Design

The direct reliability-based design method uses all available information about the basic variables, induding correlation, and does not simplify the limit state in any manner. It requires performing spectral analysis and extreme analysis of the loads. In addition, linear or nonlinear structural analysis can be used to develop a stress frequency distribution. Then, stochastic load combinations can be performed. Linear or nonlinear structural analysis can then be used to obtain deformation and stress values. Serviceability and strength failure modes need to be considered at different levels of the ship, that is, hull girder, grillage, panel, plate and detail. The appropriate loads, strength variables, and failure definitions need to be selected for each failure mode. Using reliability assessment methods such as FORM, reliability indices ~s for all modes at all levels need to be computed and compared with target reliability indices ~~s. Equation 14 gives the relationship between the reliability index ~ and the probability of failure.

19.4.3 Load and Reststance Factor Design

The second approach (LRFD) of reliability-based design consists of the requirement that a factored (reduced) strength of a structural component is larger than a linear combination of factored (magnified) load effects as given by the following general format:

$$\phi R_n \geq \sum_{i=1}^{m} \gamma_i L_{ni} \qquad [21]$$

where ϕ = strength factor, R_n = nominal (or design) strength, γ_i = load factor for the *i*th load component out of n components, and L_{ni} = nominal (or design) value for the ith load component out of m components.

In this approach, load effects are increased, and strength is reduced, by multiplying the corresponding characteristic (nominal) values with factors, which are called strength (resistance) and load factors, respectively, or partial safety factors (PSFs). The characteristic or nominal value of some quantity is the value that is used in current design practice, and it is usually equal to a certain percentile of the probability distribution of that quantity. The load and strength factors are different for each type of load and strength. Generally, the higher the uncertainty associated with a load, the higher the corresponding load factor; and the higher the uncertainty associated with strength, the lower the corresponding strength factor. These factors are determined probabilistically so that they correspond to a prescribed level of reliability or safety. It is also common to consider two classes of performance function that correspond to strength and serviceability requirements.

The difference between the allowable stress design (ASD) and the LRFD format is that the latter uses different safety factors for each type of load and strength. This allows for taking into consideration uncertainties in load and strength, and to scale their characteristic values accordingly in the design equation. ASD (or called working stress) formats cannot do that because they use only one safety factor as seen by the following general design format:

$$\frac{R}{FS} \geq \sum_{i=1}^{m} L_i \qquad [22]$$

where R = strength or resistance, L_i = load effect, and FS = factor of safety. In this design format, all loads are assumed to have average variability. The entire variability of the strength and the loads is placed on the strength side of the equation. The factor of safety FS accounts for this entire variability.

In the LRFD design format, ship designers can use the load and resistance factors in limit-state equations to account for uncertainties that might not be considere!properly by deterministic methods (that is, ADS) without explicitly performing probabilistic analysis. The LRFD format as described in this chapter is concerned mainly with the structural design of ship hull components under combinations of different effects of environmental loads acting on a ship. As was noted earlier, these loads are considered primary loads acting on the hull girder of a ship, and in most cases they control the design of various structural elements. They include load effects due to still water, waves, and dynamic vertical bending moments on the hull girder (see Figure 19.1). Other load effects such as horizontal bending moments, static (dead), live, cargo, and their combinations with the primary environmental loads can also be incorporated in an LRFD design format. The intention herein is to provide naval architects and ship designers with sample reliability-based LRFD methods for their use in both early and final design stages and for checking the adequacy of the scantlings of all structural members contributing to the longitudinal and transverse strength of ships. Equation 21 ~ives the general form of the LRFD format used in this chapter.

EXAMPLE 19.4

Given:

Suppose that the simply supported beam of Figure 19.7 has a rectangular cross sectional area as shown in Figure 19.8 below. If this beam is subjected to nominal dead (including beam weight) and live uniform loads of intensity 0.5 and 0.76 kN per centimeter *(kN/cm),* respectively, design the web depth d_w using, the LRFD design format developed in Example 19.2, and the ASD (working stress design) given by equation 22 with a factor of safety equals to 2.

Assume that the length L of the beam is 5.5 m, and the yield strength of the steel is 248 MPa.

Solution:

LRFD Design According to LRFD design philosophy, the ultimate capacity of the beam is the fully plastic flexural capacity FyZ.

Assume that the plastic neutral axis is at the base of the flange, therefore,

$$38.1(d_w) = 254(50.8) = 12903 \text{ mm}^2$$

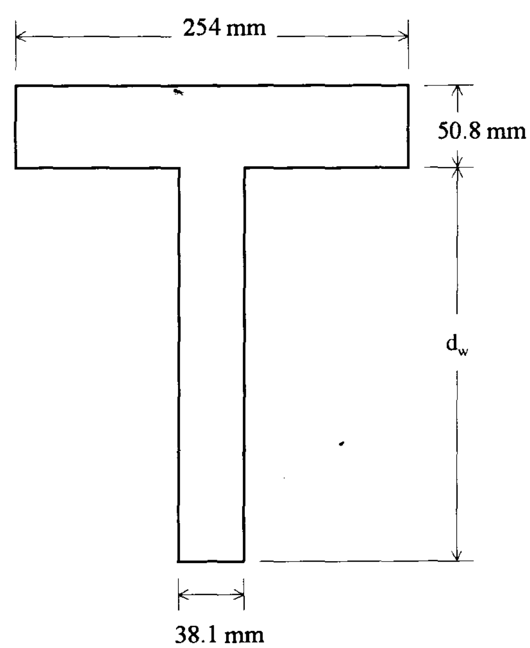

Figure 19.8 Cross Section of Simply Supported Beam for *Example 19.4*

or

$$d_w = 338.7 \text{ mm}$$

The section modulus can be computed as follows:

$$Z = 254(50.8)(25.4) + 38.1(338.7)\left(\frac{338.7}{2}\right)$$
$$= 2.51 \times 10^6 \text{ mm}^3$$

$$M_n = F_y Z = 248\left(2.51 \times 10^{-3}\right) = 623 \text{ kN} - \text{m}$$

The maximum moment for a simply supported beam is located at the mid span of the beam. Therefore, the maximum moments due to the dead and live loads are calculated as follows:

$$M_D = \frac{w_D L^2}{8} = \frac{0.5(5.5)^2}{8} \times 100 = 189 \text{ kN} - \text{m}$$

$$M_L = \frac{w_L L^2}{8} = \frac{0.76(5.5)^2}{8} \times 100 = 287 \text{ kN} - \text{m}$$

Based on the partial safety factors of the design equation of Example 19.2, the reduced strength is

$$0.93M_n = 0.93(623) = 579.4\text{kN} - \text{m}$$

and the amplified load is

$$1.11M_D + 1.24M_L = 1.11(189) + 1.24\ (287)$$
$$= 566\text{KN} - \text{m}$$
$$\therefore\ (0.93M_n = 579) > 566 \textbf{ acceptable}$$

Therefore,

$$\text{Select } d_w = 338.7.5 \text{ mm}$$

ASD Design In this design approach, the moment capacity of the beam is based on elastic strength of the beam. The elastic moment capacity of the beam is given by

$$M_y = F_y S$$

where S = elastic section modulus. In order to find S, we have to perform elastic calculations:

Assume that d_w = 340 mm., therefore,

$$\text{Area} = (254)(50.4) + (38.1)(340) = 25,756 \text{ mm}^2$$

$$\bar{y} = \frac{38.1(340)\left(\frac{340}{2}\right) + 254(50.8)(365.4)}{25,756} = 268.6 \text{ mm}$$

from tip of web.

$$I = \frac{38.1(268.6)^3}{3} + \frac{38.1(71.4)^3}{3} + \frac{254(50.8)^3}{12}$$
$$+ (254)(50.8)(96.8)^2 = 374.4 \times 10^6 \text{ mm}^4$$

$$S = \frac{I}{c} = \frac{374.4 \times 10^6}{268.6} = 1.394 \times 10^6 \text{ mm}^3$$

$$M_y = F_y S = 248\left(1.394 \times 10^{-3}\right) = 345.7 \text{ kN} - \text{m}$$

According to ASD design format of equation 22,

$$\frac{M_y}{FS} \geq (M_D + M_L = 476 \text{ kN} - \text{m})$$

$$\frac{M_y}{FS} = \frac{345.7}{2} = 172.9 \text{ kN} - \text{m}$$

$$172.9 < 476 \textbf{ unacceptable}$$

Try now d_w = 619 mm, hence

$$\text{Area} = (254)(50.8) + (38.1)(619) = 36,525 \text{ mm}^2$$

$$\bar{y} = \frac{38.1(620)\left(\frac{620}{2}\right) + 254(50.8)(645.4)}{36,525}$$
$$= 428.5 \text{ mm}$$

from tip of web.

$$I = \frac{38.1(428.5)^3}{3} + \frac{38.1(191.5)^3}{3}$$
$$+ \frac{254(50.8)^3}{12} + (254)(50.8)(216.9)^2$$
$$= 1.698 \times 10^9 \text{ mm}^4$$

$$S = \frac{I}{c} = \frac{1.698 \times 10^9}{428.5} = 3.963 \times 10^6 \text{ mm}^3$$

$$M_y = F_y S = 248\left(3.963 \times 10^{-3}\right) = 982.7 \text{ kN} - \text{m}$$

According to the ASD design format of equation 22,

$$\frac{M_y}{FS} \geq (M_D + M_L = 476 \text{ kN} - \text{m})$$

$$\frac{M_y}{FS} = \frac{982.7}{2} = 491.4 \text{ kN} - \text{m}$$

$$491.4 > 476 \textbf{ acceptable}$$

Therefore,

$$\text{Select } d_w = 619 \text{ mm.}$$

19.5 LRFD-BASED DESIGN CRITERIA FOR SHIP STRUCTURES

The design of ship structural elements is controlled by the relevant agencies and classifications societies that set up the rules and specifications. Even if ship structural design is not controlled by these specifications, the designer will probably refer to them as a guide. Ship design specifications, which are developed over the years by various organizations and classifications societies, present the best opinion of those organizations as to what represents good practice. The main objective of ship structural design is to insure safety, functional, and performance requirements of the components and the overall system of a ship. Traditionally, the so-called deterministic methods such as the allowable stress design, ASD, (also called working stress design, WSD) have been the primary methods for ship design and analyses. Because it is difficult in these methods to quantify and address uncertainties in a rational manner, and also to provide consistent levels of reliability among various structural components, there has been an increased interest in reliability-based design and analyses for ship structures. As was mentioned earlier, numerous efforts have been made to implement the theory or at least develop the basis for the analyses of some aspects of the design. This chapter is part of these efforts to provide the reader with sample reliability-based load and resistance factor design (LRFD) guidelines for surface ships.

Like any other design methods, reliability-based LRFD approach requires identifying the loads and their combinations, selecting a strength model, and the associated modes of failure of the structural component being analyzed or designed. This section provides, for demonstration purposes, the needed ingredients for the design and analysis of ship structural components through the use of partial safety factors in reliability-based LRFD formats similar to equation 21. One of the advantages of the LRFD is that it does not require performing probabilistic analysis. Ship designers can use the load and resistance factors (or called partial safety factors) in the limit-state equations to account for the uncertainties that might be considered properly by detenWnistic methods without explicitly performing reliability anmyses.

19.5.1 Design Criteria and Modes of Failure

Ship structural steel elements, like any other structural elements found in land-based structures, can fail in different modes of failure depending on the type of the element and the type of loading exerted on the that element. Failure can occur when a member or component of a structure ceases to perform the function it was designed for. Fracture is a common and important type of failure, however every failure is not due to fracture. Some failures can occur before inelastic behavior or permanent deformation of the structural component is reached. For example, it is possible for a structural component to cease to perform its function due to excessive elastic deformation. Therefore, it should be realized that failure of a member or component must be defined with reference to the function of the member or component, and not necessarily to its degree of fracture (18). Some of the more common modes of failures are summarized in Table 19.VII. A well-written design code for ship structures, whether it adopts the traditional deterministic approach for design or reliability-based LRFD format, must consider all of these failure modes in its provisions. However, it is recognized that no matter how the code or the specification are written, it is impossible to cover every possible case.

As a result, the ultimate responsibility for the design of a safe structure lies with the structural engineer.

To insure public safety and proper functioning of the structural components, modern reliability-based LRFD codes such as oftheAISC (4),AASHTO (19), and API (20) usually incorporate some of these failures modes in their provisions. As was mentioned earlier, the load and resistance factor design, or LRFD, is based on a limit states phi-

TABLE 19.VII Modes of Failures for a Structural Component 1181

Type of Failure	*Description*
Fracture	For brittle material, failure by fracture is usually sudden and complete in nature and likely to be initiated with crack in or near an area of high stress concentration. For ductile material such as steel, failure usually occurs as a result of excessive inelastic behavior (or called collapse mechanism), which leads to very large deformation long before fracture.
General Yielding	Tl\is type of failure applies to ductile material. When an element fails by general yielding, it loses its ability to support the load.
Buckling	Buckling is considered as structural stability problem. This type is the cause of failure for many structural elements that are long and cylindrical in nature. Failure by buckling can occur when a member or structure becomes unstable.
Fatigue	This type of failure is referred to as fatigue failure. It is a fracture type of failure that can be caused by repeated loading on the element or structural detail of high stress concentration, and for thousands or millions of load cycles. Usually this type failure is initiated by a crack within the element.

losophy. The limit state describes the condition at which the structural system (element) or some part of the system ceases to perform its intended function. These limit states can be classified into two categories,

1. strength limit states, and
2. serviceability limit states.

Strength limit states are based on safety consideration or ultimate load-carrying capacity of a structure and they include plastic strengths, buckling, and permanent deformation. Serviceability limit states, on the other hand, refer to the performance of a structure under normal service loads and they are concerned with the uses and functioning of the structure. They include such terms as excessive deflections, first yield, slipping, vibration, and cracking (6). Also, strength limit states require the definition of the lifetime extreme loads and their combinations, whereas serviceability limit states require annual-extreme loads and their combinations.

The LRFD specifications usually focus on very specific requirements pertaining to strength limit states and allows the engineer or designer some freedom or judgment on serviceability issues. This, off course, does not mean that the serviceability limit state is not significant; rather the life and safety of the public are considered to be the most important items (6). The modes of failure for ship structural components have serious consequences such as the entire loss of ship, loss of lives, and environmental damages (that is, water pollution in case of tankers of chemical carriers). Accordingly, only strength limit states that take into,account the ultimate capacity of ship structural element are considered in this chapter for demonstration purposes. **In** fact, most of the strength models for ship structural elements as provided in the subsequent sections are based on the ultimate strength capacity of the member, and therefore, strength limit states are used.

19.5.2 Design Loads and Load Combinations

Load determination in a random sea environment, in which a ship operates, can be a challenge to ship designers. Adequate load determination is crucial to any ship structural design effort, and must be given a great deal of considerations. When using any design code, the structural designer should be aware of any simplifying assumptions made in load calculations in order to permit recognition of those instances in which these simple models do not apply. Because of the large variety of loads that may act on a single structural member, it is sometimes important to define the conditions under which these loads occur and the frequency of their occurrences.

Loads of ship structures are categorized into two primary types (9),

1. loads due to a natural environment, and
2. loads due to a man-made environment.

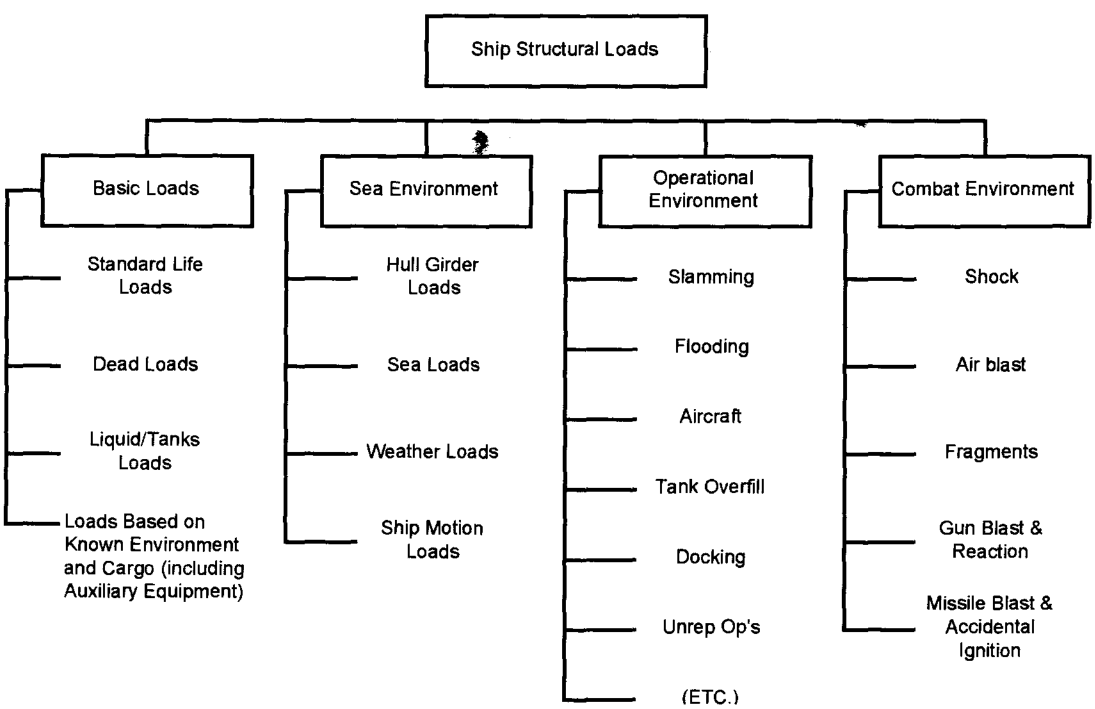

Figure 19.9 Hull Structural Load Categories

The main groups of loads for ship structures and their categories are shown in Figures 19.9. These loads are further subdivided into four main types,

1. basic loads,
2. loads due to the sea environment,
3. operational, environmental, and rare loads, and
4. loads due to combat environment.

The basic and sea-environment loads can be considered in load combinations; whereas operational and combat loads are beyond the scope of the LRFD methods presented in this chapter, and should be treated individually.

Basic or gravity loads are applied to all ship structural elements regardless of environmental influences and operational conditions. These loads include, for example, dead and live loads, liquid loads in tanks, and equipment loads. Live standard loads represent cargo, personnel, and minor equipment. Table 19.VIII provides an example distribution, intensities, and the applications of this type of load.

LiquidfTank loads are the loads that are due to the hydrostatic force caused by the head of liquid inside tanks (such as ballast, fuel, cargo, and fresh water).

The loads acting on the ship's hull girder can be categorized into three main types

1. stillwater loads,
2. wave loads, and
3. dynamic loads.

The load effect of concern herein is the vertical bending moment exerted on the ship hull girder.

TABLE 19.VIII Example Standard Live Load Distr~bution 117,22)

Type of Compartment	*Live Loading (kPa)*
Living and control space, offices and passages, main deck and above	3.6
Living spaces below main deck	4.8
Offices and control spaces below main deck	7.2
Shop spaces	9.6
Storeroom/Magazines	14.4"
Weather portions of main deck and 01 level	12.0[b]

a. Or stowage weight, whichever is greater.

b. Or maximum vehicle operating load (including helicopter operational loads), whichever is greater.

Stillwater loads can be predicted and evaluated with a proper consideration of variability in weight distribution along the ship length, variability in its cargo loading conditions, and buoyancy. Both wave loads and dynamic loads are related and affected by many factors such as ship characteristics, speed, heading of ship at sea, and sea state (waves heights). Waves height is a random variable that requires statistical and extreme analyses of ship response data collected over a period of time in order to estimate maximum wave-induced and dynamic bending moments that the ship might encounter during its life. The statistical representation of sea waves allows the use of statistical models to predict the maximum wave loads in ship's life.

Procedures for computing design wave loads for a ship's hull girder based on spectral analysis can be found in numerous references pertaining to ship structures such as Hughes (5), Sikora et al (23), and Ayyub et al. (9).

19.5.2.1 Design loads

The design load effects that are of concern in this chapter and used for developing reliability-based design ship structural elements are those load effects resulting from ship hull girder vertical bending and their combinations. As indicated earlier, the loads acting on the ship's hull girder can be categorized into three main types: still water loads, wave loads, and dynamic loads.

The calm water or still water loading should be investigated in design processes although it rarely governs the design of a ship on its own. The ship is balanced on the draft load waterline with the longitudinal center of gravity aligned with the longitudinal center of buoyancy in the same vertical plan. Then, the hull girder loads are developed based on the differences between the weights and the buoyancy distributions along the ship's length. The net load generates shear and bending moments on the hull girders. The resulting values from this procedure are to be considered the design (nominal) values in the LRFD format for the still water shear forces and bending moments on the hull girder.

Wave-induced bending moment is treated as a random variable dependent on ship's principal characteristics, environmental influences, and operational conditions. Spectral and extreme analyses can be used to determine the extreme values and the load spectra of this load type during the design life of the ship. The outcome of this analysis can be in the form of vertical or horizontal longitudinal bending moments or stresses on the hull girder. Computer programs have been developed to perform these calculations for different ships based on their types, sizes, and operational conditions (23).

Spectral and extreme analyses can be used to determine the design value of the dynamic and combined wave-induced and dynamic bending moments on a ship hull girder during its design life (23).

19.5.2.2 Load combinations and ratios

Reliability-based LRFD formats for ship structural elements presented in this chapter is based on two load combinations that are associated with correlation factors as presented in the subsequent sections (24).

The load effect on a ship hull girder or any structural element such as unstiffened or stiffened panel due to combinations of still water and vertical wave-induced bending moments is given by

$$f_c = f_{SW} + k_{WD} f_{WD} \qquad [23]$$

where f_{SW} = stress due to still water bending moment, f_{WD} = stress due to wave-induced bending moment, f_c = unfactored combined stress, k_W = correlation factor for wave-induced bending moment and can be set equal to one (24).

The load effect on ship structural element due to combinations of still water, vertical wave-induced and dynamic bending moments is given by

$$f_c = f_{SW} + k_W(f_W + k_D f_D) \qquad [24]$$

where f_W = stress due to waves bending moment, f_D = stress due to dynamic bending moment, and k_D = correlation factor between wave-induced and dynamic bending moments. The correlation factor k_D is given by the following two cases of hogging and sagging conditions (7, 22,24):

Hogging Condition:

$$k_D = \mathrm{Exp}\left[\frac{53080}{\left(158\mathrm{LBP}^{-0.2} + 14.2\mathrm{LBP}^{0.3}\right)\mathrm{LBP}}\right] \qquad [25]$$

Sagging Condition:

$$k_D = \mathrm{Exp}\left[\frac{21200}{\left(158\mathrm{LBP}^{-0.2} + 14.2\mathrm{LBP}^{0.3}\right)\mathrm{LBP}}\right] \qquad [26]$$

where LBP = length between perpendiculars for a ship in feet. Values of k_D for LBP ranging from 90 to 305 m can be obtained either from Table 19.IX or from the graphical chart provided in Figure 19.10.

19.5.3 Limit States and Design Strength

The design of ship structural component for all stations along the length of a ship should meet one of the following conditions; the selection of the appropriate equation depends on the availability of information as required by these two limit state equations:

Limit State I

$$\phi R_u \geq \gamma_{SW} f_{SW} + \gamma_{WD} k_{WD} f_{WD} \qquad [27]$$

Limit State II

$$\phi R_u \geq \gamma_{SW} f_{SW} + k_W(\gamma_W f_W + \gamma_D k_D f_D) \qquad [28]$$

where R_u = ultimate strength capacity of ship structural component (that is, force, stress, moment, etc.), ϕ = strength reduction factors for ultimate strength capacity of the structural component being analyzed, γ_{SW} = load factor for the load due to still water bending moment, f_{SW} = load effect due to still water bending moment, k_{WD} = combined wave-induced and dynamic bending moment factor, γ_{WD} = load

TABLE 19.IX Correlation Coefficient of Whipping Bending Moment (k_D) for LBP between 90 and 305 m (7, 24)

Length of Ship, LBP (meters)	$k_{D(sag)}$	$k_{D(hog)}$
27.9	0.578	0.254
37.2	0.672	0.369
46.5	0.734	0.461
55.8	0.778	0.533
65.0	0.810	0.591
74.4	0.835	0.637
83.6	0.854	0.675
92.9	0.870	0.706

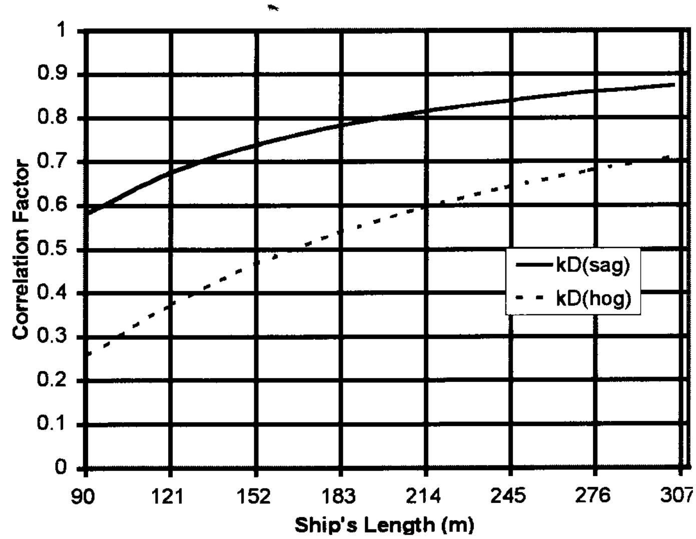

Figure 19.10 Correlation Coefficient of Whipping Bending Moment (k_D) for 90 < LBP < 305 m (7, 24)

factor for the stress due combined wave-induced and dynamic bending moment, f_{WD} = load effect due to combined wave-induced and dynamic bending moments, k_W = load combination factor, can be taken as 1.0, γ_W = load factor for the load effect due waves bending moment, f_W = load effect due to waves bending moment, k_D = load combination factor, can be taken as 0.7 or obtained from Figure 19.10 and Table 19.IX, γ_{WD} = load factor for the load effect due to dynamic bending moment, and f_D = load effect due to dynamic bending moment.

For cases of unstiffened panels where the limit state is formulated to take into account various combinations of uniaxial, biaxial, edge shear, and lateral pressure load effects, the design of these panels for all stations along the length of a ship should meet one of the following conditions:

$$\left(\frac{f_{1x}}{\phi_{R_{ux}} R_{ux}}\right)^2 + \left(\frac{f_{1y}}{\phi_{R_{uy}} R_{uy}}\right)^2 - \eta_b \left(\frac{f_{1x}}{\phi_{R_{ux}} R_{ux}}\right)\left(\frac{f_{1y}}{\phi_{R_{uy}} R_{uy}}\right) \le 1 \quad [29]$$

$$\left(\frac{f_{2x}}{\phi_{R_{ux}} R_{ux}}\right)^2 + \left(\frac{f_{2y}}{\phi_{R_{uy}} R_{uy}}\right)^2 - \eta_b \left(\frac{f_{2x}}{\phi_{R_{ux}} R_{ux}}\right)\left(\frac{f_{2y}}{\phi_{R_{uy}} R_{uy}}\right) \le 1 \quad [30]$$

$$\left(\frac{f_{1x}}{\phi_{R_{ux}} R_{ux}}\right)^2 + \left(\frac{f_{1y}}{\phi_{R_{uy}} R_{uy}}\right)^2 + \left(\frac{f_{1\tau}}{\phi_{R_{u\tau}} R_{u\tau}}\right)^2 \le 1 \quad [31]$$

$$\left(\frac{f_{2x}}{\phi_{R_{ux}} R_{ux}}\right)^2 + \left(\frac{f_{2y}}{\phi_{R_{uy}} R_{uy}}\right)^2 + \left(\frac{f_{2\tau}}{\phi_{R_{u\tau}} R_{u\tau}}\right)^2 \le 1 \quad [32]$$

where R_{ux}, and R_{uy} = ultimate strength capacity of a plate that depends on the loading conditions (that is, uniaxial stress, edge shear, etc.) for the unstiffened plate element, and $\phi_{R_{ux}}$ and $\phi_{R_{uy}}$ = strength reduction factors correspond to the ultimate strength capacity R_{ux} and R_{uy}, respectively, $\phi_{R_{u\tau}}$ = strength reduction factor for plates in shear, $R_{u\tau}$ = ultimate load capacity of plate in shear, f_{1x} = magnification of the applied stress in the x-direction for limit state I, f_{2x} = magnification of the applied stress in the x-direction for limit state II, f_{1y} = magnification of the applied stress in the y-direction for limit state I, f_{2y} = magnification of the applied stress in the y-direction for limit state II, $f_{1\tau}$ = magnification of the applied stress in the τ-direction for limit state I, $f_{2\tau}$ = magnification of the applied stress in the τ-direction for limit state II, and

$$\eta_b = \begin{cases} 0.25 & \alpha \ge 3.0 \\ 0.25 - \left(\frac{\alpha - 3}{2}\right)\left[3.2e^{-0.35B} - 2.25\right] & 1.0 < \alpha < 3.0 \\ 3.2e^{-0.35B} - 2 & \alpha = 1.0 \end{cases} \quad [33]$$

in which α = aspect ratio of plate (a/b), and B = plate slenderness ratio. The magnified stresses f_{1x}, f_{2x}, f_{1y}, f_{2y}, $f_{1\tau}$, and $f_{2\tau}$ can be determined according to the following equations:

$$f_{1x} = \gamma_{SW} f_{SWx} + k_{WD}\gamma_{WD} f_{WDx} \quad [34]$$

$$f_{2x} = \gamma_{SW} f_{SWx} + k_W(\gamma_W f_{Wx} + k_D\gamma_D f_{Dx}) \quad [35]$$

$$f_{1y} = \gamma_{SW} f_{SWy} + k_{WD}\gamma_{WD} f_{WDy} \quad [36]$$

$$f_{2y} = \gamma_{SW} f_{SWy} + k_W(\gamma_W f_{Wy} + k_D\gamma_D f_{Dy}) \quad [37]$$

$$f_{1\tau} = \gamma_{SW} f_{SW\tau} + k_{WD}\gamma_{WD} f_{WD\tau} \quad [38]$$

$$f_{2\tau} = \gamma_{SW} f_{SW\tau} + k_W(\gamma_W f_{W\tau} + k_D\gamma_D f_{D\tau}) \quad [39]$$

The nominal (that is, design) values of the strength and load components should satisfy these formats in order to achieve specified target reliability levels. The nominal strength for various structural components of a ship can be determined as described in the subsequent sections. It is to be noted that these strength models are provided herein in a concise manner without the detailed background of their bases. The interested reader should consult (9,20,22,26).

19.5.3.1 Design strength for unstiffened panels

An unstiffened panel of ship structures is basically a plate element as shown in Figure 19.4. The design strength of unstiffened panels (plates) can be computed using formulas that correspond appropriately to their loading conditions. This section provides a summary of these formulas. They must be used appropriately based on the loading conditions of the plate between stiffeners. Both serviceability and strength limit states are provided herein although only the strength limit states were considered in the paper for computing strength reduction factors.

Uniaxial compression: The ultimate strength f_u of plates under uniaxial compression stress can be computed from one of the following two cases (27,28):

For a/b > 1.0:

$$f_u = \begin{cases} F_y\sqrt{\dfrac{\pi^2}{3(1-\nu^2)B^2}} & \text{if } B \ge 3.5 \\ F_y\left(\dfrac{2.25}{B} - \dfrac{1.25}{B^2}\right) & \text{if } 1.0 \le B < 3.5 \\ F_y & \text{if } B < 1.0 \end{cases} \quad [40]$$

For a/b < 1.0:

$$f_u = F_y\left[\alpha C_u + 0.08(1-\alpha)\left(1 + \frac{1}{B^2}\right)\right]^2 \le F_y \quad [41]$$

where

F_y = yield strength (stress) of plate
a = length or span of plate
b = distance between longitudinal stiffeners,

$B = \frac{b}{t}\sqrt{\frac{F_y}{E}}$, plate slenderness ratio

$\alpha = a / b$, aspect ratio of plate

t = thickness of the plate

E= the modulus of elasticity

ν = Poisson's ratio

and

$$C_u = \begin{cases} \sqrt{\dfrac{\pi^2}{3(1-\nu^2)B^2}} & \text{if } B \geq 3.5 \\ \dfrac{2.25}{B} - \dfrac{1.25}{B^2} & \text{if } 1.0 \leq B < 3.5 \\ 1.0 & \text{if } B < 1.0 \end{cases} \quad [42]$$

Edge shear The ultimate strength $f_{u\tau}$ of plates under pure edge shear stress can be computed as:

$$F_{u\tau} = F_{cr\tau} + F_{P\tau} \quad [43]$$

where $F_{cr\tau}$ = critical or buckling stress and $F_{P\tau}$ = post-buckling strength using tension field action. The buckling strength can be computed based on one of the following three conditions that correspond to shear yield, inelastic buckling, and elastic buckling (25):

$$F_{cr\tau} = \begin{cases} F_{y\tau} & \text{if } B \leq m_1 \\ \sqrt{k_\tau \dfrac{\pi^2 F_y F_{pr}}{12(1-\nu^2)B^2}} & \text{if } m_1 < B \leq m_2 \\ k_\tau \dfrac{\pi^2 F_y}{12(1-\nu^2)B^2} & \text{if } B > m_2 \end{cases} \quad [44]$$

where $F_{y\tau}$ = yield stress in shear, F_{pr} = proportional limit in shear which can be taken as $0.8F_{y\tau}$, and

$$m_1 = \frac{\sqrt{k_\tau \dfrac{\pi^2 F_y F_{pr}}{12(1-\nu^2)}}}{F_{y\tau}} \quad [45]$$

$$m_2 = \sqrt{k_\tau \frac{\pi^2 F_y}{12(1-\nu^2)F_{pr}}} \quad [46]$$

The buckling coefficient k_τ can be obtained from Figure 2 or from the following two expressions depending on whether the plate under pure shear is simply supported or clamped, respectively:

For $\alpha \geq 1.0$:

$$k_\tau = \begin{cases} 5.35 + \dfrac{4.0}{\alpha^2} & \text{for simple supports} \\ 8.98 + \dfrac{5.6}{\alpha^2} & \text{for clamped supports} \end{cases} \quad [47]$$

For $\alpha \leq 1.0$:

$$k_\tau = \begin{cases} 4.0 + \dfrac{5.35}{\alpha^2} & \text{for simple supports} \\ 5.6 + \dfrac{8.98}{\alpha^2} & \text{for clamped supports} \end{cases} \quad [48]$$

The yield stress in shear ($F_{y\tau}$) is given by

$$F_{y\tau} = \frac{F_y}{\sqrt{3}} \quad [49]$$

where F_y = yield stress of plate. The post-buckling shear strength $F_{P\tau}$ is given by

$$F_{P\tau} = \frac{F_y - \sqrt{3}F_{cr\tau}}{2\sqrt{1+\alpha^2}} \quad [50]$$

where α is the aspect ratio of plate (a/b). If the aspect ratio α exceeds 3.0, tension field action is not permitted. In this case, the ultimate shear strength of a plate shall be based on elastic and inelastic buckling theory such that:

$$F_{u\tau} = F_{cr\tau} \quad [51]$$

where $F_{cr\tau}$ can be computed from equation 44.

Lateral pressure: The ultimate strength f_{up} of plates under lateral pressure is given as (12):

$$f_{up} = \frac{2222F_y^2}{EB^2}\left[\left(\frac{\frac{w_u}{b}}{\left[0.004 + 0.02\tanh\left(\frac{B}{60}\sqrt{\frac{E}{F_y}}\right)\right]}\right)^{\frac{1}{3}} + 1\right] \quad [52]$$

where F_y = yield strength (stress) of plate, b = distance between longitudinal stiffeners, or plate width, B = slenderness ratio of plate, α = aspect ratio of plate, a = length or span of plate, t = thickness of the plate, E = the modulus of elasticity, and w_u = specified permanent set. Values for the ratio of the permanent set to plate width (w_u/b) or the permanent set to plate thickness (w_u/t) varies with both the ma-

TABLE 19.X Ranges of the Ratio w_u/b (17)

Aluminum or Steel Type	*Yield Strength F_y (MPa)*	*Top Side*	*Lower Shell/Tank*	*Flooding/Damage Control*
AL5086	193.0	0.000	0.000	0.009
AL5456	227.5	0.000	0.001	0.032
M_S	234.4	0.000	0.009	0.128
HTS	324.0	0.000	0.006	0.098
HY80	552.0	0.000	0.001	0.021
HY100	690.0	0.000	0.000	0.019

TABLE 19.XI Ranges of the Ratio w_u/t (17)

Aluminum or Steel Type	*Yield Strength F_y (ksi)*	*Top Side*	*Lower Shell/Tank*	*Flooding/ Damage Control*
AL5086	193.0	0.000	0.005	0.821
AL5456	227.5	0.000	0.066	2.792
MS	234.4	0.002	0.801	11.282
HTS	324.0	0.001	0.553	8.658
HY80	552.0	0.000	0.114	1.822
HY100	690.0	0.000	0.037	1.692

terial type and the location of a plate within the ship. When using equation. 52, these values can be obtained from Tables 19.X and XI, respectively.

Biaxial compression: The ultimate strength f_{ux} and f_{uy} of plates under biaxial compression stresses should meet the requirement of following interaction equation (12,29):

$$\left(\frac{f_x}{f_{ux}}\right)^2 + \left(\frac{f_y}{f_{uy}}\right)^2 - \eta_b\left(\frac{f_x}{f_{ux}}\right)\left(\frac{f_y}{f_{uy}}\right) \le 1 \qquad [53]$$

where η_b as defined by equation 33, $\alpha = a/b$, the aspect ratio of plate, f_x = the applied stress in the x-direction, f_y = the applied stress in the y-direction, f_{ux} = the ultimate strength of a plate under compressive normal stress in the x-direction acting alone, and f_{ux} = the ultimate strength of a plate under compressive normal stress in the y-direction acting alone.

The ultimate stresses f_{ux} and f_{uy} can be computed from equations 40 and 41, respectively. It should be noted that when using equations 40 and 41 for calculating both f_{ux} and f_{uy}, the length of plate a, is assumed to coincide with the *x*-direction and the aspect ratio α is greater than unity. If, however, α is less than unity, then f_{ux} and f_{uy} should be interchanged in equations 40 and 41.

Biaxial compression and edge shear: The ultimate strength f_{ux}, f_{uy}, and $f_{u\tau}$ of plates under biaxial compression and edge shear stresses should meet the requirement of following interaction equation as adopted by the API (20) and the DnV (30):

$$\left(\frac{f_x}{f_{ux}}\right)^2 + \left(\frac{f_y}{f_{uy}}\right)^2 + \left(\frac{f_\tau}{f_{u\tau}}\right)^2 \le 1 \qquad [54]$$

where f_x = the applied stress in the *x*-direction, f_y = the applied stress in the *y*-direction, f_τ = the applied shear stress, f_{ux} = the ultimate strength of a plate under compressive normal stress in the *x*-direction acting alone, f_{ux} = the ultimate strength of a plate under compressive normal stress in the *y*-direction acting alone, and $f_{u\tau}$ = the ultimate shear stress when the plate is subjected to pure edge shear. The ultimate stresses f_{ux}, f_{uy}, $f_{u\tau}$ can be computed from equations 40, 41, and 43, respectively.

Other load combinations with lateral pressure: The loading conditions for unstiffened plates that are covered in this chapter are the combined in-plane and lateral pressure loads. Lateral pressure in combination with the other cases of loading presented in the previous sections can lead to a number of loading conditions that can have an effect on the overall strength of plates. In such situations, the designer should consider the following cases:

- lateral pressure and uniaxial compression,
- lateral pressure and biaxial compression,
- lateral pressure, uniaxial compression and edge shear,
- lateral pressure, biaxial compression and edge shear, and
- lateral pressure and edge shear.

The effect of lateral pressure on the ultimate strength of plates subjected to in-plane loads is so complex that there are no simple models (formulas) available to predict the strength of plates under these types of loading. However, there are design charts available for some of these load combinations. For example, large deflection solutions for case 4 (lateral pressure, biaxial compression, and edge shear) exits, but the results cannot be put in the form of a simple formula as those given in the previous sections. Researchers demonstrated that the lateral pressure has negligible effect on both the uniaxial and biaxial compressive strength of plates when *bIt* is less than 50. However, for values of the ratio *bIt* greater than 50, the lateral pressure can have a negative impact on the biaxial strength (case 2). Also, they pointed out that a clear understanding of the influence of pressure on strength of plates subjected to in-plane loads is lacking and that additional testing and research on the subject deemed to be appropriate to clarify some of the aspects involved. Therefore, it is recommended to treat lateral pressure as an uncoupled load from other in-plane loads, and to design for them individually and separately.

9.5.3.2 Design strength for stiffened and gross panels

A stiffened and gross panel of ship structures is basically a stiffened panel element as shown in Figure 19.3. The design strength of stiffened and gross panels can be cOIlliuted using formulas that correspond appropriately to their"ioading conditions. In this section, a summary of selected strength models that are deemed suitable for LRFD design formats is presented. These strength models are for longitudinally stiffened panels subjected to uniaxial stress and combined uniaxial stress with lateral pressure. Three strength models for stiffened panels that are deemed appropriate for reliability-based LRFD format are those of Herzog (31), Hughes (5), and Adamchak (32). Herzog's model can be applied for stiffened panel under axial stress loading, while both Hughes and Adamchak models are suitable for predicting the ultimate strength of stiffened panel when it is subjected to combined axial stress and lateral pressure. A formula for performing reliability (safety) checking on the design of gross panel, which is based on the transverse and longitudinal stiffness of stiffeners, is also provided. These strength models are presented herein in a concise manner, and they were evaluated in terms of their applicability, limitations, and biases with regard to ship structures. A complete review of the models used by different classification agencies such as the AISC (4), ASSHTO (19), and the API (20) is provided in (17,22).

Axial compression: Based on reevaluation of 215 tests by various researchers and on empirical formulation, Herzog (31) developed a simple model (formula) for the ultimate strength of stiffened panels that are subjected to uniaxial compression without lateral loads. The ultimate strength F_u of a longitudinally stiffened plate is given by the following empirical formula (31):

$$F_u = \begin{cases} m\bar{F}_y\left[0.5 + 0.5\left(1 - \dfrac{ka}{r\pi}\sqrt{\dfrac{\bar{F}_y}{E}}\right)\right] & \text{for } \dfrac{b}{t} \le 45 \\ mc_1\bar{F}_y\left[0.5 + 0.5\left(1 - \dfrac{ka}{r\pi}\sqrt{\dfrac{\bar{F}_y}{E}}\right)\right] & \text{for } \dfrac{b}{t} > 45 \end{cases} \quad [55]$$

where

$\bar{F}_y = \dfrac{F_{ys}A_s + F_{yp}A_p}{A_s + A_p}$, mean yield strength for the entire plate-stiffener cross section

F_{yp} = yield strength of plating

F_{ys} = yield strength of stiffener

E = modulus of elasticity of stiffened panel

A_p = bt, cross sectional area of plating

$A_s = t_f f_w + t_w d_w$, cross sectional area of stiffener

$A = A_s + A_p$, cross sectional area of plate-stiffener

t_f = stiffener flange thickness

f_w = stiffener flange width or breadth

t_w = stiffener web thickness

d_w = stiffener web depth

a = length or span of longitudinally stiffened panel

b = distance between longitudinal stiffeners

t = plate thickness

I = moment of inertia of the entire cross section

$r = \sqrt{\dfrac{I}{A}}$, radius of gyration of entire cross section

m = corrective factor accounts for initial deformation and residual stresses

k = buckling coefficient depends on the panel end constraints

$c_1 = 1 - 0.007\left(\dfrac{b}{t} - 45\right)$

Values for m and k for use in equation 55 can be obtained from Tables 19.XII and XIII, respectively.

The 215 tests evaluated by Herzog belong to three distinct groups. Group I (75 tests) consisted of small values

TABLE 19.XII Recommended m Values (31)

Degree of Imperfection and Residual Stress	m
No or average imperfection and no residual stress	1.2
Average imperfection and average residual stress	1.0
Average or large imperfection and high value for residual stress	0.8

TABLE 19.XIII Recommended k Values (31)

End Condition	k
Both ends are simply-supported	1.0
One end is simply-supported and the other is clamped	0.8
Clamped ends	0.65

TABLE 19.XIV Statistics of 215 Tests Conducted on Longitudinally Stiffened Plates in Uniaxial Compression (31)

Group	*Number of Tests*	*Mean Value* (μ)	*Standard Deviation* (σ)	*COV*
I	75	1.033	0.134	0.130
II	64	0.999	0.100	0.100
III	76	0.981	0.162	0.169
All	215	1.004	0.136	0.135

for imperfection and residual stress, Group II (64 tests) had average values for imperfection and residual stress, while the third group (Group III, 76 tests) consisted of higher values for imperfection and residual stress. The statistical uncertainty *(COV)* associated with Herzog model of equation 55 is 0.218. The mean value μ, standard deviation σ, and *COV* of the measurement to prediction are given in Table 19.XIV.

Axial compression and lateral pressure: According to Hughes (5), there are three types of loading that must be considered for determining the ultimate strength of longitudinally stiffened panels. These types of loading are:

1. lateral load causing negative bending moment of the plate-stiffener combination (the panel),
2. lateral load causing positive bending moment of the panel, and
3. in-plane compression resulting from hull girder bending.

The sign convention to be used throughout this section is that of Hughes (5). Bending moment in the panel is considered positive when it causes compression in the plating and tension in the stiffener flange, and in-plane loads are positive when in compression (Figure 19.11). The deflection, w_0, due to the lateral load (that is, lateral pressure) Mo and initial eccentricity, δ_0 is considered positive when they are toward the stiffener as shown in Figure 19.11. In beam-column theory, the expressions for the moment Mo and the corresponding deflection w_0 are based upon an ideal column, which is assumed to be simply supported.

Disregarding plate failure in tension, there can be three distinct modes of collapse (Figure 19.11) according to Hughes (5), 1) compression failure of the stiffener (Mode I Collapse), 2) compression failure ofthe plating (Mode II Collapse), and 3) combined failure of stiffener and plating (Mode III Collapse).

The ultimate axial strength (stress) F_u for a longitudinally stiffened panel under a combination of in-plane compression and lateral loads (including initial eccentricities) can be, therefore, defined as the minimum of the collapse (ultimate) values of applied axial stress computed from the expressions for the three types (modes) of failure. Mathematically, it can be given as

$$F_u = \min(F_{a,uI},\ F_{a,uII}\ \text{and}\ F_{a,uIII}) \qquad (56)$$

where $F_{a,uI}$, $F_{a,uII}$ and $F_{a,uIII}$ correspond to the ultimate collapse value of the applied axial stress for Mode I, Mode II, and Mode III, respectively. The mathematical expressions for the collapse stress for each mode of failures are provided in references 5 and 24.

Adamchak (32) developed a model in 1979 to estimate the ultimate strength of conventional surface ship hulls or hull components under longitudinal bending or axial compression. The model itself is very complex for hand calculation and therefore it is not recommended for use in a design code without some computational tools or a computer program. To overcome the computational task for this model, Adamchak developed a computer program (ULTSTR) based on this model to estimate the ductile collapse strength of conventional surface ship hulls under longitudinal bending.

The recent version of the ultimate strength (ULTSTR) program is intended for preliminary design and based on a variety of empirically based strength of material solutions for the most probable ductile failure modes for stiffened

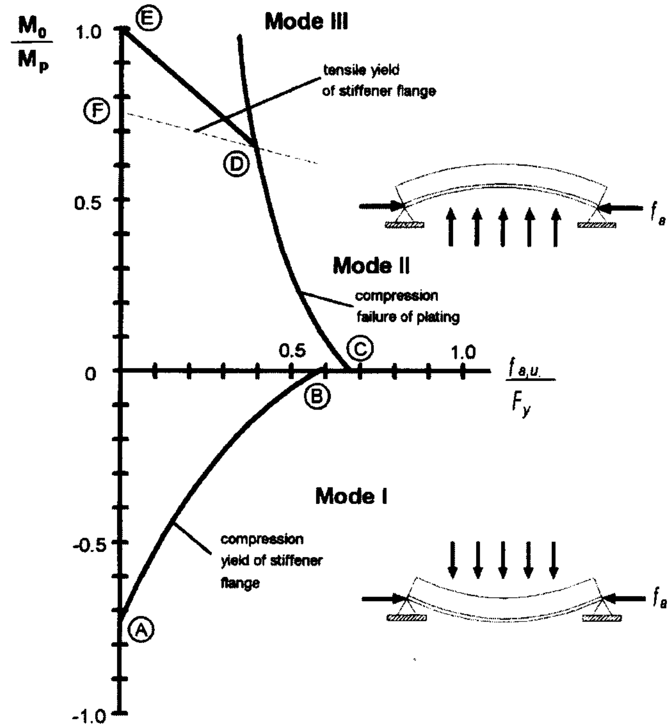

Figure 19.11 Interaction Diagram for Collapse Mechanism of a Stiffened Panel under Lateral and In-plane Loads (5)

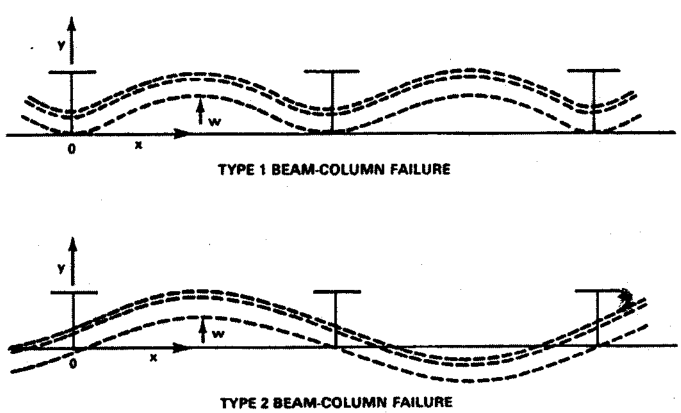

Figure 19.12 Types of Beam-column Failure (2)

and unstiffened plate structures. The probable ductile failure modes include section yielding or rupture, inter-frame Euler beam-column buckling, and inter-frame stiffener tripping (lateral-torsional buckling). The program also accounts for the effects of materials having different yield strength in plating and stiffeners, for initial out-of-plane distortion due to fabrication, and for lateral pressure loading.

The basic theory behind this model (or ULTSTR) originated preliminary in a joint project on ship structural design concepts involving representatives of the Massachusetts Institute of Technology (MIT), the Ship Structural Committee (SSC), and navy practices in general. Longitudinally stiffened panel elements can fail either by material yielding, material rupture (tension only), or by some form of structural stability. The instability failure modes for this model include Euler beam-column buckling and stiffener lateral torsional buckling (tripping). Euler beam-column buckling is actually treated in this model as having two distinct types of failure patterns as shown in Figure 19.12. Type I is characterized by all lateral deformation occurring in the same direction. Although this type of failure is depended on all geometrical and material properties that define the structural element, it is basically yield strength dependent. Type I failure is assumed to occur only when either lateral pressure or initial distortion, or both, are present. On the other hand, Type II failure is modulus (E) depended, as far as initial buckling is concerned. This type of failure can be initiated whether or not initial distortion or lateral pressure, or both, are present. Type III failure is a stiffener tripping or lateral-torsional buckling.

Therefore, the ultimate axial strength (stress) for longitudinally stiffened panel under various types ofloading (including material fabrication distortion) is the minimum value of the axial compressive stress computed from the expressions for the three types (modes) of failures, that is:

$$F_u = \min(F_{uI}, F_{uII} \text{ and } F_{uIII}) \qquad [57]$$

Detailed mathematical expressions for the three modes of failures as implemented in the program ULTSTR can be found in references 17 and 33.

Gross panels and grillages: To perform a a reliability (safety) checking on the design of gross panel, the reduced ratio of the stiffness orthe transverse and longitudinal stiffeners should at least equal to the load effect given by the geometrical parameters shown in the second hand term of the following expression:

$$\phi_g \frac{I_y}{I_x} \geq \frac{(n+1)^5}{n\pi^2\left(0.25 + \frac{2}{N^3}\right)}\left(\frac{b}{a}\right)^5 \qquad [58]$$

where I_x = moment of inertia of longitudinal plate-stiffener, I_y= moment of inertia of transverse plate-stiffener, a = length or span of the panel between transverse webs, b = distance between longitudinal stiffeners, n = number of longitudinal stiffeners, N = number of longitudinal subpanels in overall (or gross) panel, and ϕ_g = gross panel strength reduction factor. A target reliability level can be selected based on the ship type and usage. Then, the corresponding safety factor can be looked up from Table 19.XXI.

19.5.3.3 Design strength for hull girder

The ultimate bending strength capacity for a section at any station can be estimated using the incremental strain approach by calculating the moment-curvature relationship and as the maximum resisting moment for the section. This approach calculates the moment-curvature relationship and the ultimate bending capacity of a ship's hull girder cross section using strength and geometry information about scantlings of all structural members contributing to the longitudinal strength. The ultimate strength for hull girder can be given as (13)

$$Mu = cFuZ \qquad [59]$$

where Z = section modulus of the hull and c = is a buckling knockdown factor. The buckling knockdown factor c is equal to the ultimate collapse bending moment of the hull, taking buckling into consideration, divided by the initial yield moment (13).

The ultimate collapse moment can be calculated using a nonlinear finite element program such as ULTSTR or using software based on the Idealized Structural Unit Method (13). Approximate nonlinear buckling analysis may also be used. The initial yield moment is simply equal to the yield strength of the material multiplied by the section modulus of the hull at the compression flange, that is, at deck in sagging condition, or at bottom in hogging condition. The default values for the buckling knockdown factor c may be taken as 0.80 for mild steel and 0.60 for high-strength steel.

19.5.3.4 Fatigue strength

Assessment of ship structural capacity for fatigue and fracture was provided in greater detail in Chapter 19. This section summarizes fatigue strength in the context of structural reliability. Reliability-based LRFD design format lquires the use of partial safety factors (PSFs) in the limit state equations. The PSFs are both for strength and load variables. They are commonly termed strength reduction and load amplification factors.

The structural detail or joint element of a ship should meet the following performance functions or limit state:

$$\gamma_{S_e} S_e \leq \left[\frac{n_i}{\phi_A A \gamma_{k_s}^b k_s^b \phi_\Delta \Delta_L} \right]^{\frac{1}{b}} \qquad [60]$$

where

$$S_e = \sqrt[m]{\sum_{i=1}^{n_b} f_i S_i^m} \qquad [61]$$

S_e = Miner's equivalent stress range,
ϕ_Δ = reduction safety factor corresponds to fatigue damage ratio Δ_L,
ϕ_A = reduction safety factor corresponds to the intercept of the S-N curve,
γ_{k_s} = amplification safety factor for fatigue stress uncertainty, and
γ_{S_e} = amplification safety factor for Miner's rule equivalent stress range.

It is to be noted that the nominal Se is the best estimate resulting from spectral analysis. The nominal (that is, design) values of the fatigue variables should satisfy these formats in order to achieve specified target reliability levels.

The probabilistic characteristics and nominal values for the strength and load components were determined based on statistical analysis, recommended values from other specifications, and by professional judgment. These factors are determined using structural reliability methods based on the probabilistic characteristics of the basic random variables for fatigue including statistical and modeling (or prediction) uncertainties. The factors are determined to meet target reliability levels that were selected based on assessing previous designs. This process of developing reliability-based LRFD rules based on implicit reliability levels in current practices is called code calibration.

The LRFD design for fatigue, as given by equation 61, requires partial safety factors and nominal values. The partial safety factors (PSF's) are provided in Tables 19.xXIII and XXIV according to the following requirements:

- Target reliability levels in the range from 2.0 to 4.0,
- Fatigue strength prediction methods based on Miner's linear cumulative damage theory and on the characteristic S-N curve, and
- Selected details of the British standards (BS 5400).

A target reliability level should be selected based on the ship class and usage. Then, the corresponding partial safety factors can be looked up from Tables 19.XXIII and 19.XXIV based on the appropriate detail for joint for selected details. Similar tables can be developed for other details.

19.5.4 LRFD-based Partial Safety Factors for Ship Structural Components

19.5.4.1 Load factors

This section provides load factors for different categories of hull structural members. The factors can be used in the limit state equations for the design of these elements, and also for checking the adequacy of their strength capacity. The load factors are tabulated by load type and load combinations for selected target reliability levels ~os as shown in Table 19.xVII. The ranges of target levels depend on the type of structural member under investigation. Recommended target reliability levels for various hull structural elements are provided in Table 19.xVIII.

The factors are provided for the load effect of still water SW, wave-induced W, dynamic D, and combined wave-induced and dynamic WD bending moments for target reliability levels (~o) ranging from 3.0 to 6.0. These load factors can be used in the limit states and the load combinations presented in Section 19.5.3. The target reliability, ~o' should be selected based on the ship type and usage. Then, the corresponding load factors can be looked up from Table 19.xV for the load combination of interest.

19.5.4.2 Strength factors

This section gives strength (resistance) factors for different categories of hull structural members. The factors can be used in the limit state equations for the design of these elements, and also for checking the adequacy of their strength capacity. The strength factors can be used in the limited states as provided in Section 19.4.3 for hull girders, unstiffened, stiffened, and gross panels, respectively. Recommended target reliability levels for the design of these vari,ous hull structural components are provided in Table 19.XVI.

Tables 19.xVII through 19.XXll provide nominal strength reduction factors for the design of unstiffened, stiffened, and gross panels; and hull girders and fatigue details of ship structures. These factors can be used in the strength limit state equations as provided in Section 19.5.3.

TABLE 19.XV Nominal Load Factors

Target Reliability Index (β_o)	*Load Factors*			
	γ_{SW}	γ_W	γ_D	γ_{WD}
3.0	0.74	1.40	1.10	1.45
3.5	0.74	1.55	1.10	1.50
4.0	0.74	1.70	1.10	1.55
4.5	0.74	1.90	1.10	1.60
5.0	0.74	2.05	1.10	1.63
5.5	0.74	2.30	1.10	1.66
6.0	0.74	2.50	1.10	1.70

TABLE 19.XVI Recommended Target Reliability Levels (B_0) for Reliability-based LRFD Format

Structural System or Element	*Ranges of* β_0
Hull girder collapse	4.0–6.0
Unstiffened panel	3.0–4.0
Stiffened panel	3.5–4.5
Gross panel	2.0–3.0
Fatigue	2.0–4.0

19.6 EXAMPLES: DESIGN AND ANALYSIS

The following examples demonstrate the use of LRFD-based partial safety in the limit state equations for designing and checking the adequacy of structural components of a ship:

EXAMPLE 19.5: UNSTIFFENED PANEL DESIGN

Given:

A 122-cm x 61-cm x t unstiffened plate element is to be designed at the bottom deck of a ship to withstand a uniaxial compression stress due to environmental bending moment loads acting on the ship. The stresses due to the environmental loads are estimated to have the following values: 82.7 MPadue to still water bending, 33.1 MPadue to waves bending, and 12.4 MPa due to dynamic bending. If the yield strength of steel is 235 MPa, design the thickness t of the plate assuming target level of 3.0.

Solution:

For unstiffened pane.l under uniaxial compression, the strength is given by equation 40 as

$$f_u = \begin{cases} F_y\sqrt{\dfrac{\pi^2}{3(1-\nu^2)B^2}} & \text{if } B \geq 3.5 \\ F_y\left(\dfrac{2.25}{B}-\dfrac{1.25}{B^2}\right) & \text{if } 1.0 \leq B < 3.5 \\ F_y & \text{if } B < 1.0 \end{cases}$$

Assume that t = 6.5 mm, and the modulus of elasticity for steel is 190 GPa, therefore

$$B = \frac{b}{t}\sqrt{\frac{F_y}{E}} = \frac{61}{0.65}\sqrt{\frac{235}{200,000}} = 3.22$$

and

TABLE 19.XVII Nominal Strength Factors for Unstiffened Panels

		Strength Factors (ϕ) and Target Reliability Index (β)					
		3.0		3.5		4.0	
Loading Condition	*EQ.*	ϕ	ϕ_τ	ϕ	ϕ_τ	ϕ	ϕ_τ
Uniaxial Compression	27	0.75	N/A	0.70	N/A	0.64	N/A
	28	0.83	N/A	0.79	N/A	0.79	N/A
Edge Shear	27	N/A	0.70	N/A	0.64	N/A	0.59
	28	N/A	0.77	N/A	0.73	N/A	0.68
Lateral Pressure	27	0.39	N/A	0.36	N/A	N/A	0.34
	28	0.47	N/A	0.46	N/A	0.44	N/A
Biaxial Compression	29	0.54	N/A	0.40	N/A	0.29	N/A
	30	0.61	N/A	0.51	N/A	0.42	N/A
Biaxial Compression and Edge Shear	31	0.68	0.70	0.60	0.64	0.53	0.59
	32	0.84	0.77	0.82	0.73	0.80	0.68

TABLE 19.XVIII Nominal Strength Factors for Stiffened Panels

		Strength Factors (ϕ) and Target Reliability Index (β_0)		
Loading Condition	*Limit State Equation*	*3.5*	*4.0*	*4.5*
Axial Compression	1	0.56	0.51	0.46
	2	0.61	0.57	0.54
Axial Compression and Lateral Loads	1	0.61	0.54	0.50
	2	0.66	0.61	0.58

TABLE 19.XIX Nominal Partial Safety Factor for the Stiffness Ratios of Gross Panels

Target Reliability Index (β_0)	*Gross Panel Strength Reduction Factor (ϕ_g)*
2.0	0.82
2.5	0.78
3.0	0.75

TABLE 19.XX Nominal Strength Factors for Hull Girders

	Target Reliability Index (β_0)				
Limit State Equation	4.0	4.5	5.0	5.5	6.0
1	0.62	0.58	0.53	0.50	0.46
2	0.70	0.67	0.63	0.62	0.58

TABLE 19.XXI Nominal Partial Safety Factors for Category B of the British Standards (BS 5400)

β_0	ϕ_Δ	ϕ_A	γ_{ks}	γ_S
2.0	0.55	0.60	1.09	1.10
2.5	0.48	0.53	1.11	1.12
3.0	0.42	0.48	1.13	1.15
3.5	0.37	0.43	1.15	1.18
4.0	0.32	0.38	1.17	1.21

TABLE 19.XXII Nominal Partial Safety Factors for Category W of the British Standards (BS 5400)

β_0	ϕ_Δ	ϕ_A	γ_{ks}	γ_S
2.0	0.52	0.57	1.07	1.08
2.5	0.45	0.50	1.09	1.10
3.0	0.39	0.45	1.11	1.12
3.5	0.34	0.40	1.13	1.15
4.0	0.29	0.35	1.14	1.17

$$f_u = F_y\left(\frac{2.25}{B} - \frac{1.25}{B^2}\right)$$

$$= 235\left(\frac{2.25}{3.22} - \frac{1.25}{(3.22)^2}\right) = 135.9 \text{ MPa}$$

The design of the plate should meet the requirement of the reliability-based LRFD format and the partial safety factors as given in Tables 19.XV and XVII for the limit state under consideration and the appropriate partial safety factors for $\beta_0 = 3.0$, that is,

$$\phi f_u = \gamma_{SW} f_{SW} + k_W (\gamma_W f_W + \gamma_D k_D f_D)$$
$$\phi f_u = 0.83(135.9) = 112.8 \text{ MPa}$$

$$\gamma_{SW} f_{SW} + k_W (\gamma_W f_W + \gamma_D k_D f_{SW})$$
$$= (1.05)(82.7) + (1)[1.4 (33.1) + (1.1)(0.7) (12.4)]$$
$$= 142.7 \text{ MPa}$$

(ϕf_u = 112.8 ksi) < 142.7 MPa; this is **unacceptable**

Try a value of t = 10 mm., therefore

$$B = \frac{b}{t}\sqrt{\frac{F_y}{E}} = \frac{61}{1.0}\sqrt{\frac{235}{200,000}} = 2.1$$

and

$$f_u = F_y\left(\frac{2.25}{B} - \frac{1.25}{B^2}\right)$$

$$= 235\left(\frac{2.25}{2.1} - \frac{1.25}{(2.1)^2}\right) = 185.2 \text{ MPa}$$

$$B = \frac{b}{t}\sqrt{\frac{F_y}{E}} = \frac{61}{0.65}\sqrt{\frac{235}{200,000}} = 3.22$$

$$\phi f_u = 0.83(185.2) = 153.7 \text{ MPa}$$

$$\gamma_{SW} f_{SW} + k_W (\gamma_W f_W + \gamma_D k_D f_{SW})$$
$$= (1.05)(82.7) + (1)[1.4 (33.1) + (1.1) (0.7) (12.4)]$$
$$= 142.7 \text{ MPa}$$

(ϕf_u = 185.2 MPa) > 142.7 MPa; this is **acceptable**

Hence, select PL: 122 × 61 × 1 cm

EXAMPLE 19.6: ADEQUACY CHECKING FOR UNSTIFFENED PANEL

Given:

Suppose that the unstiffened plate element of Example 19.5 is to be checked for the effect of lateral pressure. Would this plate be adequate to withstand the lateral pressure generated by the environmental loads?.

Solution:

For unstiffened panel under pure lateral pressure, the strength is given by equation 52 as

$$f_{up} = \frac{2222 F_y^2}{EB^2}\left[\left(\frac{\frac{w_u}{b}}{\left[0.004 + 0.02\,tanh\left(\frac{B}{60}\sqrt{\frac{E}{F_y}}\right)\right]}\right)^{\frac{1}{3}} + 1\right]$$

For MS Steel, and Lower Shell/Tank, Table 19.X gives

$$\frac{w_u}{b} = 0.009$$

With B = 2.1 as computed in Example 19.5, therefore,

$$f_{up} = \frac{2222\ (235)^2}{200,000(2.1)^2} \times \left[\left(\frac{0.009}{\left[0.004 + 0.02\, tanh\left(\frac{2.1}{60}\sqrt{\frac{200,000}{235}}\right)\right]}\right)^{\frac{1}{3}} + 1\right]$$

$$= 247 \text{ MPa}$$

The design of the plate should meet the requirement of the LRFD method and the partial safety factors as given in Tables 19.XV and XVII for the limit state under consideration and the appropriate partial safety factors for $\beta_0 = 3.0$, that is,

$$\phi f_{up} \geq \gamma_{SW} f_{SW} + k_W (\gamma_W f_W + \gamma_D k_D f_D)$$

$$\phi f_{up} = 0.47(247) = 116.1 \text{ MPa}$$

$$(1.05)(82.7) + (1)[1.4(33.1) + (1.1)(0.7)(12.4)] = 142.7 \text{ MPa}$$

($\phi f_u = 116.1$ MPa) < 142.7 MPa; this is **unacceptable**

Hence, the plate will not be adequate for lateral pressure. A new plate should be designed.

EXAMPLE 19.7: STIFFENED PANEL DESIGN

Given:

A stiffened panel, pinned at the ends, whose dimensions are shown in Figure 19.13 is to be designed at th~ bottom deck of a ship to withstand a uniaxial compressi~h stress due to environmental bending moment loads acting on the ship. The stresses due to the environmental loads are estimated to have the following values: 1.035 MPa due to still-water bending, 31.0 MPa due to waves bending, and 15.2 MPa due to dynamic bending. If the yield strength of steel is 235 MPa for the plating and 248 MPa for the stiffener (that is, web & flange), and the dimensions ofthe panel are as shown in Table 19.XXIII, design the thickness t and length a of the plating assuming a target reliability level of 4.0. Note that the length ofthe plating is not to exceed 195 cm, and not to be less than 122 cm.

Solution

For stiffened panel under uniaxial compression without lateral pressure, the strength model as given by equation 19.55 (Herzog) applies.

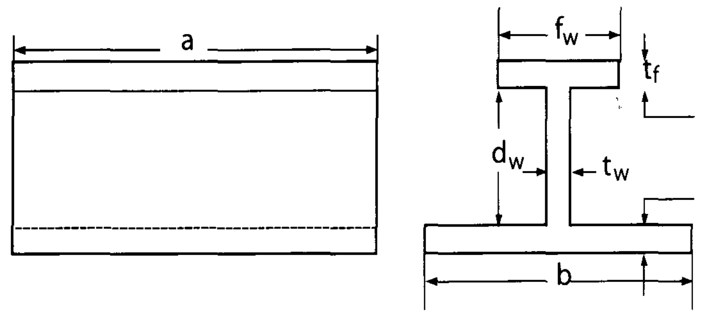

Figure 19.13 Stiffened Panel Design

$$F_u = \begin{cases} m\bar{F}_y\left[0.5 + 0.5\left(1 - \frac{ka}{r\pi}\sqrt{\frac{\bar{F}_y}{E}}\right)\right] & \text{for } \frac{b}{t} \leq 45 \\ m\bar{F}_y\left[0.5 + 0.5\left(1 - \frac{ka}{r\pi}\sqrt{\frac{\bar{F}_y}{E}}\right)\right] & \\ \times\left[1 - 0.007\left(\frac{b}{t} - 45\right)\right] & \text{for } \frac{b}{t} > 45 \end{cases}$$

Assume an initial value for t = 0.5 cm, and for a = 195 cm, hence

$$A_p = bt = 61(0.5) = 30.5 \text{ cm}^2$$

$$A_s = t_f f_w + t_w d_w = 0.95(4.5) + 0.52(11.5) = 10.26 \text{ cm}^2$$

$$\bar{F}_y = \frac{F_{ys}A_s + F_{yp}A_p}{A_s + A_p} = \frac{248(10.26) + 235(30.5)}{10.26 + 30.5} = 338.3 \text{ MPa}$$

Check the slenderness ratio b/t:

$$\frac{b}{t} = \frac{61}{0.5} = 122 > 45$$

Therefore, the following equation applies:

$$F_u = m\bar{F}_y\left[0.5 + 0.5\left(1 - \frac{ka}{r\pi}\sqrt{\frac{\bar{F}_y}{E}}\right)\right] \times \left[1 - 0.007\left(\frac{b}{t} - 45\right)\right]$$

The radius of gyration r for the cross section can be found when the moment of inertia I has been established. To compute I, the location of neutral axis must be calculated:

TABLE 19.XXIII Given Dimensions of the Stiffened Panel

Variable	*Value (cm)*
Width of plating, b	61.0
Stiffener web depth, d_w	11.50
Stiffener flange breadth, f_w	4.5
Stiffener web thickness, t_w	0.52
Stiffener flange thickness, t_f	0.95

$$\bar{y} = \frac{1}{10.26+30.5}\left[\frac{0.5}{2}(61)(0.5) + \left(0.5+\frac{11.5}{2}\right)(11.5)(0.52) + \left(0.5+11.5+\frac{0.95}{2}\right)(0.95)(4.5)\right]$$
$$= 2.41 \text{ cm from the base of the plating.}$$

Therefore, $I = 717.2\ \text{cm}^4$, and

$$r = \sqrt{\frac{I}{A}} = \sqrt{\frac{717.2}{10.26+30.5}} = 4.2\text{cm}$$

Assuming m and k both equal to one (see Tables 19.XII and XIII), we have

$$F_u = (1)(338.3) \times \left[0.5 + 0.5\left(1 - \frac{205}{(4.2)\pi}\sqrt{\frac{338.3}{200,000}}\right)\right] \times \left[1 - 0.07\left(\frac{61}{0.5} - 45\right)\right] = 106.1 \text{ MPa}$$

In reference to Tables 19.XVII and XX, and for a target reliability index $\beta_0 = 4.0$ as given, the following partial safety factors are obtained for use in the design equation:

$$\phi = 0.57,\ \gamma_{SW} = 1.05,\ \gamma_W = 1.7,\ \text{and}\ \gamma_D = 1.1$$

Therefore,

$$\phi F_u = 0.57(106.1) = 60.5 \text{ MPa}$$

$$\gamma_{SW} f_{SW} + k_W(\gamma_W f_W + \gamma_D k_D f_D)$$
$$= (1.05)(1.035) + (1)[1.7(31) + (1.1)(0.7)(15.2)]$$
$$= 65.5 \text{ MPa}$$

($\phi F_u = 60.5$ MPa) < 65.5 MPa; this is **unacceptable**

Now try t = 0.65 cm and a =195 cm, hence,

$$A_p = bt = 61(0.65) = 39.7 \text{ cm}^2$$

$$A_s = t_f f_w + t_w d_w = 10.26 \text{ cm}^2$$

$$\bar{F}_y = \frac{F_{ys}A_s + F_{yp}A_p}{A_s + A_p} = \frac{248(10.26) + 235(39.7)}{10.26+39.7}$$
$$= 337.7 \text{ MPa}$$

Check the slenderness ratio b/t:

$$\frac{b}{t} = \frac{61}{0.65} = 94 > 45$$

Therefore, the following equation applies:

$$F_u = m\bar{F}_y\left[0.5 + 0.5\left(1 - \frac{ka}{r\pi}\sqrt{\frac{\bar{F}_y}{E}}\right)\right] \times \left[1 - 0.007\left(\frac{b}{t} - 45\right)\right]$$

Again, the radius of gyration r for the cross section can be found when the moment of inertia I is established. To compute I, the location of neutral axis must be calculated:

$$\bar{y} = \frac{1}{10.26+30.5} \times \left[\frac{0.65}{2}(61)(0.5) + \left(0.65+\frac{11.5}{2}\right)(11.5)(0.52) + \left(0.65+11.5+\frac{0.95}{2}\right)(0.95)(4.5)\right]$$
$$= 2.1 \text{ cm from the base of the plating.}$$

Therefore, $I = 758.4\ \text{cm}^4$, and

$$r = \sqrt{\frac{I}{A}} = \sqrt{\frac{758.4}{10.26+39.7}} = 3.9\text{cm}$$

Assuming m and k both equal to one (see Tables XII and XIII), we have

$$F_u = (1)(337.7) \times \left[0.5 + 0.5\left(1 - \frac{205}{(3.9)\pi}\sqrt{\frac{337.7}{200,000}}\right)\right] \times \left[1 - 0.007\left(\frac{61}{0.65} - 45\right)\right]$$
$$= 145.8 \text{ MPa}$$

$$\phi F_u = 0.57(145.8) = 83.1 \text{ MPa}$$

$$= \gamma_{SW} f_{SW} + k_W (\gamma_W f_W + \gamma_D k_D f_D)$$
$$= (1.05)(1.035) + (1)[1.7(31) + (1.1)(0.7)(15.2)]$$
$$= 65.5 \text{ MPa}$$

$(\phi F_u = 83.1$ MPa $) > 65.5$ MPa; this is **acceptable**

Hence, select t = 6.5 mm, and a = 195 cm

EXAMPLE 19.8: ADEQUACY CHECKING FOR GROSS PANEL

Given:

Assume a target reliability level of 2.5, check the adequacy of the following gross panel:

$$I_x = 666 \text{ cm}^4$$
$$I_y = 1103 \text{ cm}^4$$
$$N = 5$$
$$n = 3$$
$$a = 152 \text{ cm}$$
$$b = 61 \text{ cm}$$

Solution:

For gross panel, the strength is given by equation 19.58 as

$$\phi_g \frac{I_y}{I_x} \geq \frac{(n+1)^5}{n\pi^2\left(0.25 + \frac{2}{N^3}\right)}\left(\frac{b}{a}\right)^5$$

For target reliability index of 2.5, Table 19.XXI gives $\phi_g = 0.78$, therefore,

$$\phi_g \frac{I_y}{I_x} = 0.78\frac{1103}{666} = 1.29$$

$$\frac{(n+1)^5}{n\pi^2\left(0.25 + \frac{2}{N^3}\right)}\left(\frac{b}{a}\right)^5$$

$$= \frac{(3+1)^5}{(3\pi^2)\left(0.25 + \frac{2}{(5)^3}\right)}\left(\frac{61}{152}\right)$$

$$= 1.35$$

Since 1.29 < 1.35, the gross panel will be **inadequate**.

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Chapter 19 Appendix: First-Order Reliability Method

The First-Order Reliability Method (FORM) is a convenient tool to assess the reliability of a ship structural element. It also provides a means for calculating the partial safety factors ⟠ and Yi that appear in Equation 1 for a specified target reliability level ~o. The simplicity of the first-order reliability method stems from the fact that this method, beside the requirement that the distribution types must be known, requires only the first and second moments; namely the mean values and the standard deviations of the respective random variables. Knowledge of the joint probability density function (PDF) of the design basic variables is not needed as in the case of the direct integration method for calculating the reliability index ~. Even if the joint PDF of the basic random variables is known, the computation of ~ by the direct integration method can be a very difficult task.

In design practice, there are usually two types of limit states: the ultimate limit states and the serviceability limit states. Both types can be represented by the following performance function:

$$g(X) = g(X_1, X_2, \ldots, X_n) \qquad [AI]$$

in which X is a vector of basic random variables $(X_1, X_2, \ldots, X_n)$ for the strengths and the loads. The performance function g(X) is sometimes called the limit state function. It relates the random variables for the limit-state qf interest. The limit state is defined when g(X) = 0, and th~refore, failure occurs when g(X) < 0 (see Figure 19.AI). The reliability index ~ is defined as the shortest distance from the origin to the failure surface in the reduced coordinates at the most probable failure point (MPFP) as shown in Figure 19.Al.

As indicated in this chapter, the basic approach for developing reliability-based design guidelines and rules requires the determination of the relative reliability of designs based on current practices. Therefore, reliability assessment of existing structural components of ships such as the hull girder and its structural elements is needed to estimate a representative value of the reliability index ~. The first-order-reliability method is very well suited to perform such a reliability assessment. The following are computational steps as described in [3] for determining ~ using the FORM method:

1. Assume a design point x_i^* and obtain $x_i'^*$ in the reduced coordinate using the following equation:

$$x_i'^* = \frac{x_i^* - \mu_{X_i}}{\sigma_{X_i}} \qquad [A2]$$

where, $x_i'^* = \alpha_i^* \beta$, μ_{X_i} = mean value of the basic random variable, and σ_{X_i} = standard deviation of the basic random variable. The mean values of the basic random variables can be used as initial values for the design points. The notation x^* and x'^* are used respectively for the design point in the regular coordinates and in the reduced coordinates.

2. Evaluate the equivalent normal distributions for the non-normal basic random variables at the design point using the following equations:

$$\mu_X^N = x^* - \Phi^{-1}\left(F_X(x^*)\right)\sigma_X^N \qquad [A3]$$

and

$$\sigma_X^N = \frac{\left(\Phi^{-1}\left(F_X(x^*)\right)\right)}{f_X(x^*)} \qquad [A4]$$

where μ_X^N = mean of the equivalent normal distribution, σ_X^N = standard deviation of the equivalent normal distribution, $F_X(x^*)$ = original (non-normal) cumulative distribution function (CDF) of X_i evaluated at the design point, $f_X(x^*)$ = original probability density function (PDF) of X_i evaluated at the design point, $\Phi(\cdot)$ = CDF of the standard normal distribution, and $\phi(\cdot)$ = PDF of the standard normal distribution.

3. Compute the directional cosines at the design point (α_i^*, i = 1,2, ..., n) using the following equations:

$$\alpha_i^* = \frac{\left(\dfrac{\partial g}{\partial x_i'}\right)_*}{\sqrt{\sum_{i=1}^{n}\left(\dfrac{\partial g}{\partial x_i'}\right)_*^2}} \quad \text{for } i = 1, 2, \ldots, n \qquad [A4]$$

where

$$\left(\frac{\partial g}{\partial x_i'}\right)_* = \left(\frac{\partial g}{\partial x_i}\right)_* \sigma_{X_i}^N \qquad [A5]$$

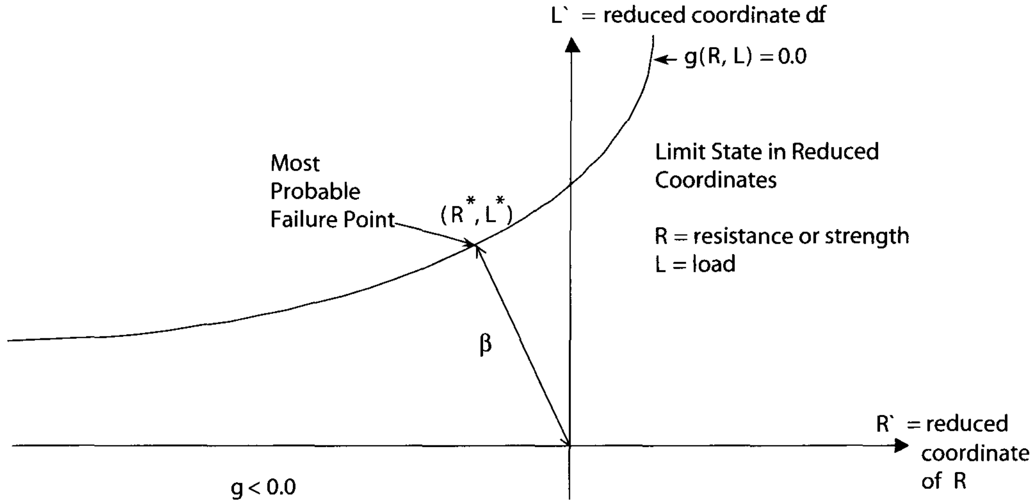

Figure 19.A1 Space of Reduced Random Variables Showing the Reliability Index and the Most Probable Failure Point

4. With α_i^*, $\mu_{X_i}^N$, and $\sigma_{X_i}^N$ now known, the following equation can be solved for the root β:

$$g\left[\left(\mu_{X_1}^N - \alpha_{X_1}^* \sigma_{X_1}^N \beta\right), \ldots, \left(\mu_{X_n}^N - \alpha_{X_n}^* \sigma_{X_n}^N \beta\right)\right] = 0 \quad [A6]$$

5. Using the β obtained from step 4, a new design point can be obtained from the following equation:

$$x_i^* = \mu_{X_i}^N - \alpha_i^* \sigma_{X_i}^N \beta \quad [A7]$$

6. Repeat steps 1 to 5 until a convergence of β is achieved. The reliability index is the shortest distance to the failure surface from the origin in the reduced coordinates as shown in Figure A1.

The important relation between the probability of failure and the reliability (safety) index is given by Equation 14.

A.1 PROCEDURE FOR CALCULATING PARTIAL SAFETY FACTORS (PSF) USING FORM

The first-order reliability method (FORM) can be used to estimate partial safety factors such those found in the design format of Equation 21. At the failure point (R^*, L_1^*, ..., L_n^*), the limit state of Equation 21 can be rewritten as

$$g = R^* - L_1^* - \ldots - L_n^* = 0 \quad [A8]$$

or, in a general form

$$g(X) = g(x_1^*, x_2^*, \ldots, x_n^*) = 0 \quad [A9]$$

For given target reliability index β_0, probability distributions and statistics (means and standard deviations) of the load effects, and coefficient of variation of the strength, the mean value of the resistance and the partial safety factors can be determined by the iterative solution of Equations A2 through A7. The mean value of the resistance and the design point can be used to compute the required mean partial design safety factors as follows:

$$\phi = \frac{R^*}{\mu_R} \quad [A10]$$

$$\gamma_i = \frac{L_i^*}{\mu_{L_i}} \quad [A11]$$

The strength factors are generally less than one, whereas the load factors are greater than one.

A.2 DETERMINATION OF A STRENGTH FACTOR FOR A GIVEN SET OF LOAD FACTORS

In developing design code provisions for ship structural components, it is sometimes necessary to follow the current design practice to insure consistent levels of reliability over various types of ship structures. Calibrations of existing design codes is needed to make the new design formats as simple as possible and to put them in a form that is familiar to the users or designers. Moreover, the partial safety factors for the new codes should provide consistent levels of reliability. For a given reliability index ~ and probability characteristics for the resistance and the load effects, the partial safety factors determined by the FORM approach might be different for different failure modes for the same structural component. Therefore, the calculated partial safety factors (PSFs) need to be adjusted in order to maintain the same values for all loads at different failure modes by the strength factor ϕ for a given set of load factors. The following algorithm can be used to accomplish this objective:

- For a given value of the reliability index β, probability distributions and statistics of the load variables, and the coefficient of variation for the strength, compute the mean strength needed to achieve the target reliability using the first-order reliability method as outlined in the previous sections.
- With the mean value for R computed in step 1, the partial safety factor can be revised for a given set of load factors as follows:

$$\phi` = \frac{\sum_{i=1}^{n} \gamma`_i \mu_{L_i}}{\mu_R} \quad [A12]$$

where = revised strength factor, and μ_R are the mean values of the loads and strength variables, respectively; and, $\gamma`_i$ = 1, 2, ..., n, are the given set of load factors.

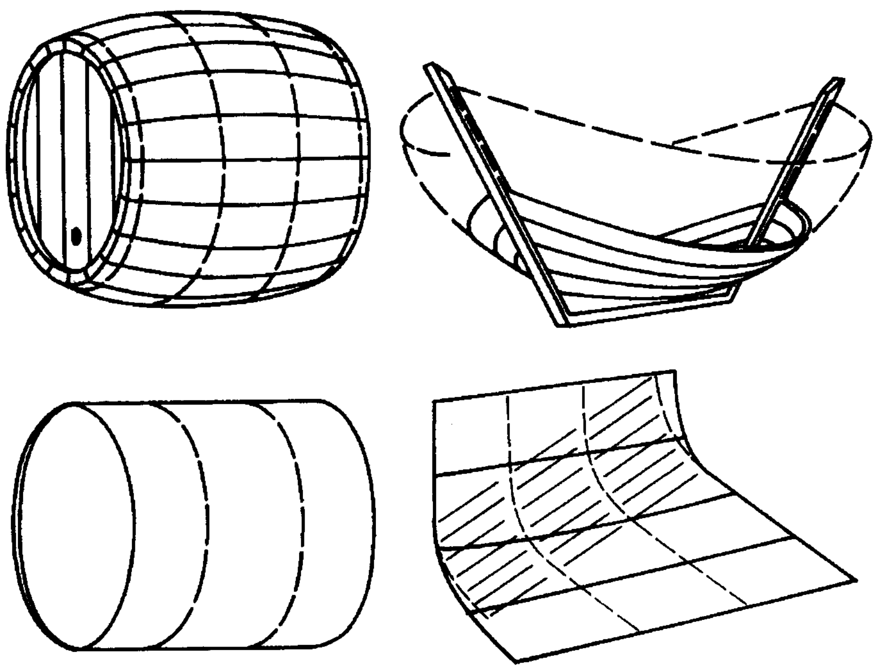

Figure 20.1 Design for Wood versus Design for Steel for Barrels and Ships

CHAPTER 20

Hull Materials and Welding

Volker Bertram and Thomas Lamb

20.1 INTRODUCTION

20.1.1 General

This chapter is an update of the corresponding chapter in the previous edition of this book (1). This is possible because much of the material has not changed. This is not to suggest that there have been no significant changes in the materials used in ship construction or in the welding processes used to join the many parts of a ship together. Where such changes have been introduced over the past 20 years they are addressed.

Structural design requires a solid understanding of materials, production processes (Chapter 25), loads and structural behavior (Chapter 18). Progress in materials and production methods has always (with some delay) resulted in changes in structural design. A classical example is the faired shape of wooden ships towards hulls avoiding double curvatures and maximizing flat plates in largely rqtotized steel shipbuilding (Figure 20.1). Often, the introduction of a new type of design drives the development of a new type material or analysis to permit the new design to achieve a safe life. By the early 2000s, shipbuilders are faced with continuous innovation, such as laser welding, adhesive bonding, and composites.

20.1.2 Materials in Shipbuilding

To meet the challenges presented by new developments, the ship designer must understand and apply principles from metallurgy, welding engineering, nondestructive testing, and the materials sciences. Knowledge ofthe basic principles of these fields will provide more efficient and reliable ship structural designs through selection of appropriate design details, material selection, joining, and quality assurance requirements. This chapter cannot completely cover all aspects of the subject, but the references can be read to deepen the designer's knowledge.

The following materials are predominantly used in shipbuilding:

- rolled plain steel for usual applications (plates and profiles for ship hull, foundations, etc.),
- rolled special steel (high-tensile steels, low-temperature steels e.g. for LNG tankers, corrosion resistant steel for product tankers, non-magnetic steel for compass area),
- cast steel (parts of rudder, stern, stem),
- forged steel (parts of the equipment like anchors, chains, rudder shaft),
- nonferrous metals, particularly aluminum (compass area, superstructure, boats) and copper-nickel alloys (pipes), and
- plastic and wood (interior equipment, boats, pipes).

Steel continues to be the dominant material for shipbuilding despite increasing use of alternative materials such as aluminum, fiber-reinforced plastics (FRP), and other composite materials. Table 20.1 by Wilckens (2) gives examples of steel plate consumption for some ship types. Material costs (2002) are typically, (2):

- \$ 500/ton for shipbuilding steel,
- \$ 2900/ton aluminum,
- \$ 7500/ton FRP, and
- \$ 15 OOO/toncomposites.

The higher value materials are predominantly used for high-speed craft, yachts and naval ships. In the former So-

TABLE 20.1 Typical Steel Plate Consumption and Material Thickness for Several Ship Types

	Required plates	*Plate thickness*
Tanker (280 000 tdw)	42 000 t	13–58 mm
Tanker (200 000 tdw)	28 000 t	13–55 mm
Bulker (150 000 tdw)	20 000 t	14–55 mm
Tanker (120 000 tdw)	17 000 t	12–48 mm
Containership (4500 TEU)	14 000 t	13–78 mm
LNG tanker (50 000 tdw)	11 000 t	9–48 mm
Containership (1000 TEU)	5000 t	12–65 mm

viet Union, titanium was used as a shipbuilding material, particularly for submarines. Titanium has also been used on some highly loaded hydrofoil joints, but is otherwise far too expensive.

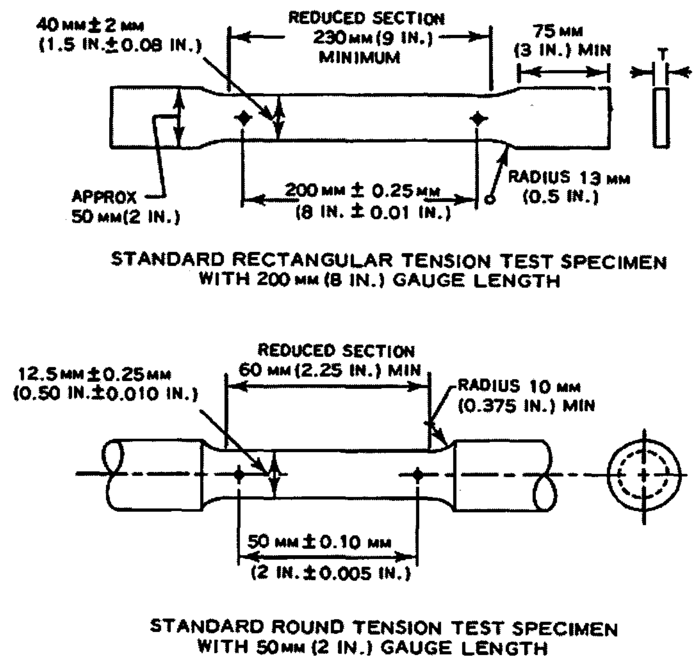

Figure 20.2 Typical Tension Test Specimens (1)

20.2 MATERIAL PROPERTIESAND TESTS

20.2.1 Tensile Properties

The most commonly used properties for design calculations and material acceptance are determined from the tensile test. Specimens and procedures for tensile testing vary between different products. Those described in this chapter are applicable to hull steel plate. Classification Societies Rules and Navy specifications generally provide applicable requirements for conventional designs. For other materials and/or for more complete requirements and details, read the American Society for Testing and JJ.aterials (ASTM) specifications E8 and A370 covering the test methods applicable to the specific material of concern. Figure 20.2 shows typical tensile specimens (rectangular 200 mm gage length and round 50 mm gage length). Figure 20.3 shows the behavior of such specimens under applied load. Gage refers to the distance between two marks punched onto the specimen prior to tensile test.

When a tensile load is applied to a specimen, it produces a proportional amount of stretching (the engineering term is strain) between the gage points. The maximum unit stress at which the strain remains directly proportioned to the stress is known as the *proportional* or *elastic limit,* and marks the upper limit of elastic strain.

The slope of the stress-strain plot from zero to the elastic limit represents the modulus of elasticity. Short duration elastic strain returns to zero when the stress returns to zero. Proportional and elastic limit tests are not usually required in structural material production testing, but are useful to designers.

As stress increases above the proportional limit, a given increase in stress produces a relatively greater amount of strain. For ordinary strength structural steels, a stress is reached where an increase in strain occurs without any increase in stress. In some cases a decrease in stress may occur as the material stretches. The stress at the first point of increased strain without increased stress is designated as the *yield point.* Not all materials have this behavior. Alternate methods for determining conformity to a yield point requirement, which are generally accepted in testing normal strength hull steel, are the divider, extension under load, and drop of the beam methods.

Materials such as high-strength steels and non-ferrous alloys do not exhibit a definite (yield) point at which strain occurs without increased stress. For these materials, a related value of yield strength is pertinent. Yield strength is the unit stress (force/area) at which a material exhibits a specified limiting deviation from the proportionality of stress to strain; the strain is usually expressed in terms of a 0.2% offset or as a 0.5% extension (strain) under load.

Tensile strength refers to the maximum unit tensile stress that a material is capable of sustaining. It is calculated from the maximum load divided by the original cross sectional area of the specimen. Percent elongation and reduction in area are calculated on the percent difference in gage length or cross section area, respectively, of the specimen before and after test. Tensile strength is independent of specimen dimension. Percent elongation and percent reduction in area are highly dependent upon gage lengths and specimen dimensions and should be determined with specimens of appropriate standard dimensions.

20.2.2 Material Tests

The *bend test* is a qualitative method of measuring ductility in which a specimen is bent around a mandrel of a specified diameter. The bend test has been eliminated as a hull steel specification requirement, although it is still widely used for evaluation of weld joints in procedure and operator qualification tests. In such tests a rectangular bar is bent around a mandrel, which varies in diameter depending on the elongation requirement for the weldment. The higher the strength, the greater the diameter. For ordinary strength steels a 38 mm wide by 9.5 mm thick specimen and a 19 mm radius mandrel are used.

Hardness tests determine the hardness of steel is determined by indenting the surface with an indenter having a specific geometry under a specific load, and measuring the resultant impression. A softer material will indent more than a harder material. The *Brinell Test* measures the diameter of the impression made by a steel ball. The Rockwell test indicates the hardness directly from the depth of an impression from a diamond cone or steel ball indenter. In both tests, different loads and indenters are used for different hardness levels. Both tests may be used to estimate tensile strength in steels, to check the uniformity of a material, to indicate the thermal effects of heat treating or welding on the base metal, as well as to determine hardness where abrasion is of concern. Table 20.11 indicates the general relationship bet'¥.een hardness values and tensile strength of steel. As all the ~andard hardness tests methods measure *suiface hardness,* there can be inaccuracies in relating these values to the material strength. Materials with surface hardness treatments, such as cold rolling, carburizing, nitriding and thermal surface hardening, may have tensile strength values lower than predicted using the comparisons shown in Table 20.11. Designers are cautioned to use tensile testing to determine the strength of materials, not hardness testing.

Fatigue tests determine fatigue properties of a material (see Chapter 18 - Analysis and Design of Ship's Structure).

A wide variety of specimens ranging from the small rotating beam and flat cantilever (Kraus) specimens to full-scale models are used in fatigue testing. Fatigue tests are usually limited to base material and individual welds. Due to the stochastic nature of fatigue, it is necessary to test always several specimens, particularly for welded structures. Fatigue tests for ship structures are by nature limited to relatively small details, which already require considerable effort to test. The fatigue life of laboratory material specimens and real ship structures of complex three-dimensional design and multi-axial stress conditions may differ considerably.

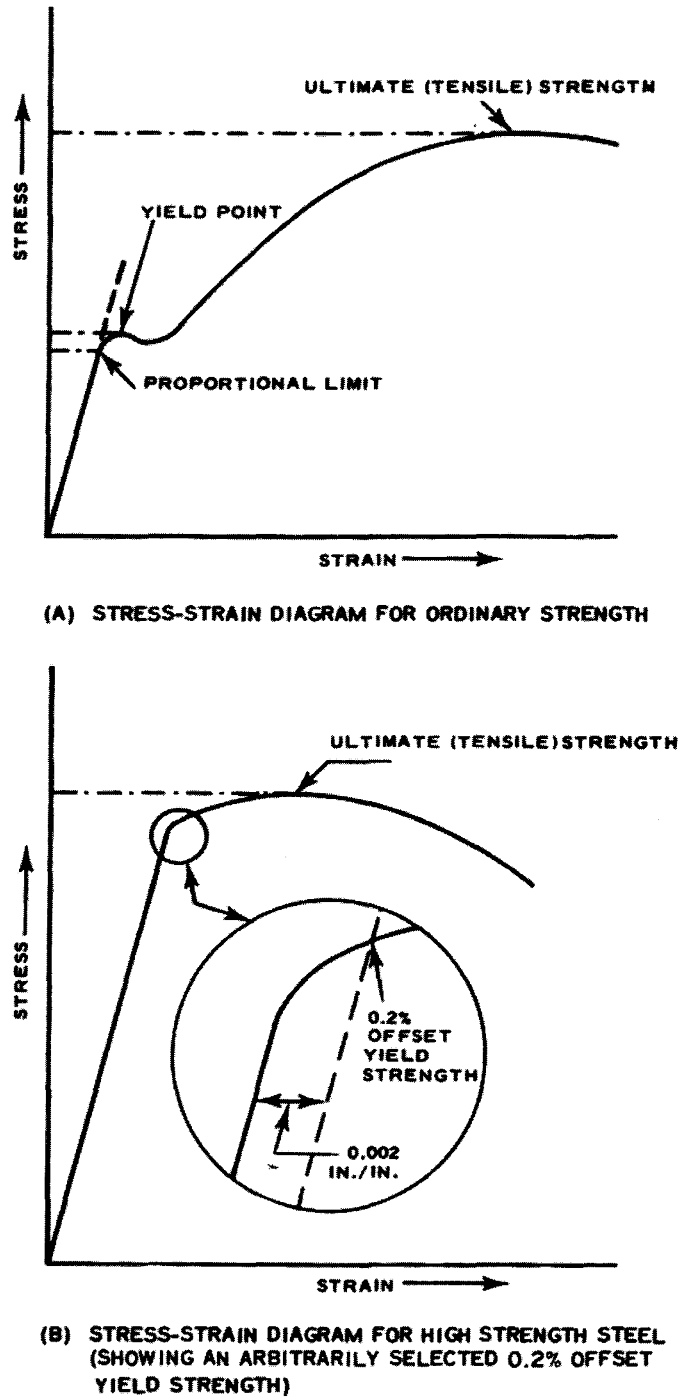

Figure 20.3 Stress-Strain Graphs of Ordinary Steel (top) and High-strength Steel (bottom) (1)

TABLE 20.II Approximate Relationship Between Hardness and Tensile Strength of Steel

	Hardness		*Tensile Strength*
Brinell[1]	*Rockwell B*[2]	*Rockwell C*[3]	*MPa*
293	—	31	1000
285	—	30	965
273	—	28	931
262	—	27	896
255	—	26	862
245	—	24	827
235	99	22	793
224	97	21	758
217	96	—	724
207	95	—	690
197	93	—	655
187	91	—	621
173	88	—	586
163	85	—	552
154	82	—	517
143	79	—	483
130	72	—	448
121	70	—	414

1. Brinell Hardness for No. 10 mm Standard Ball.
2. Rockwell B using 100 Kg load & 1.6 mm Ball.
3. Rockwell C using 150 Kg load & Brale Penetrator.

20.2.3 Toughness Properties

Investigations of brittle fractures in ship hulls during World War II revealed that steel which fractures in a fibrous (ductile) mode with the absorption of a large amount of energy will, at some lower temperature, fracture in a crystalline (brittle) mode with the absorption of very little energy (Figure 20.4). The range in which the fracture mode changes from ductile to brittle is referred to as the transition temperature range. Within this range a specific transition temperature value is determined by an arbitrary level of performance in a selected *toughness test.* Numerous tests have been devised to measure transition temperature and relate transition temperature and energy absorption to service performance. Transition temperature, however, is not a material constant since it is influenced by factors such as

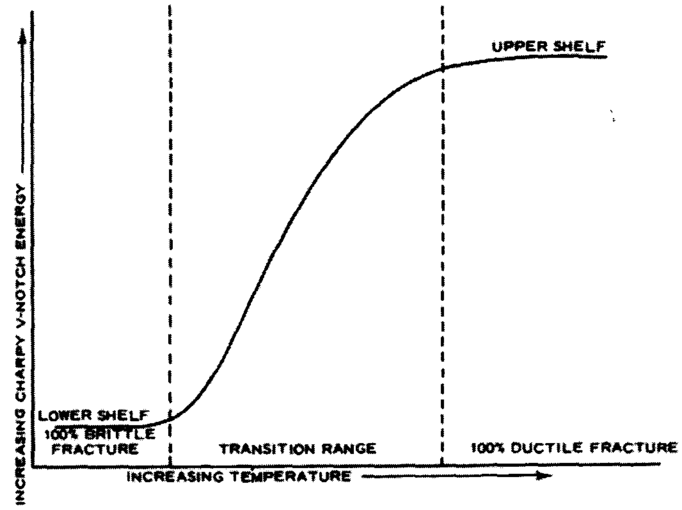

Figure 20.4 Idealized Charpy V-notch Energy Curve (1)

rate of loading, notch acuity, flaw size, structural and local restraint, alloy microstructure, and nature of the loading. Prevailing practice is to use an empirically established toughness criterion that can be related to service performance.

The *Charpy V-notch Test* (CVN) is the most widely used empirical toughness test and forms the basis for evaluation of many ship steels. An extensive background of CVN data is available which relates hull steel toughness to service performance. In addition, it is a rapid, simple and economical test that is accepted worldwide. A disadvantage of the CVN test is that it is only indirectly related to fracture mechanics concepts and cannot be used quantitatively in design. Also, the significance of a specific test energy value varies for different families of alloys and strength levels. However, because of its advantages, the CVN test is the principal toughness test specified for materials and welds in shipbuilding as well as in most structural and pressure vessel codes.

The CVN specimen is supported as a cantilever beam and broken by a single blow of a swinging pendulum weight released from a fixed height. The difference between the initial height of the weight and the height to which it rises after breaking the specimen is a measure of the energy absorbed in breaking the specimen. In some instances the lateral expansion of the specimen in the area of the fracture may be used as the criterion. In general, for a given steel and strength level, lateral expansion will be proportional to energy absorbed. Fracture surface percentage appearing crystalline may also be reported for information. CVN values are sensitive to plate rolling direction (higher parallel to rolling direction, lower transverse to rolling direction).

In the *Drop Weight Test* (DWT), the specimen with a notched brittle crack starter bead is subjected at various test temperatures to an impact load from a falling weight. The highest temperature at which a crack forms and propagates to a specimen edge is defined as the nil-ductility temperature. The nil-ductility temperature represents the highest temperature at which a material will exhibit brittle performance in the presence of a small flaw at low levels of applied stress. For normal strength hull steels, at a temperature approximately 33°C above nil-ductility temperature, the applied stress must generally exceed yield strength for fracture propagation; at approximately 67°C above nil-ductility temperature, fractures are fully ductile when tensile strength is exceeded. The Drop Weight Test is often accepted as an alternative to the CVN test. Some of the factors that limit its use are:

- test facilities are not as available as for the CVN tests,
- it does not provide information as to energy absorption, and
- the background of service-related experience is not as extensive as that of the CVN.

In addition, anomalous behavior may occur in a material, which develops a tough heat-affected zone (HAZ) at the edge of the crack-starter weld bead used in the test. The principal advantage of the test is that it can accurately establish the *nil-ductility* temperature on a wide variety of ferritic steels. This nil-ductility temperature is more directly related to design analyses involving fracture mechanics concepts.

The need to characterize fractures and fatigue crack propagation in terms of parameters which could be incorporated into design analyses, such as stress and flaw size, has generated a variety of tests derived from fracture mechanics principles. A number of such tests have been applied to jhip structure research. *Special fracture mechanics tests* are particularly useful for evaluating new hull materials or new material applications where correlative data between the CVN properties and service performance is insufficient or not available. Special fracture mechanics tests have been used for evaluating suitability of candidate high strength-to-weight ratio steel, aluminum and titanium alloys. Special tests have been used for predictions of crack growth in 9% nickel steel and aluminum for tanks in liquefied natural gas carriers, the estimation of crack arrest capabilities of various steels, and for some failure analyses.

The *Dynamic Tear* (DT) *Test* has proven to be a convenient and useful test to characterize fracture behavior. The test measures the energy absorbed in fracturing a specimen held at a specified temperature by a falling weight or swinging pendulum. Relationships have been developed between DT fracture energy values and the stress intensity factor KId for dynamic or impact loading. KId can be related mathematically to applied dynamic stress, crack geometry, crack size, and the configuration in the immediate vicinity of the crack front. Using the DT test energy at a given temperature (such as the lowest expected service temperature), the designer can estimate the tolerable flaw size for structural members at an assumed dynamic stress. Conversely the design stress level appropriate for an assumed flaw size in the structure could also be calculated.

Another test used extensively in hull structural materials research is the *Crack Opening Displacement* (COD) test. This test applies a static load to the specimen. It can be used to establish a critical stress intensity factor KIc' This factor can be used in static loading relationships in the same manner as KId is used for dynamic loading.

In addition, *large-scale tests* such as the explosion tear test, explosion bulge test and various notched wide-plate tests have been used to study fracture.

Steel transition temperature increases with loading rates. A steel which exhibits a ductile performance and high fracture-energy absorption at a given temperature at a slow loading rate may fracture in a brittle manner with little or no energy absorption with a faster rate of imposition of the same load at a different temperature. Similar differences in fracture performance are associated with increases in notch acuity. These factors should be taken into account in comparing results of different fracture toughness tests, and in projecting results of such tests to service performance.

20.3 STRUCTURAL STEELS

20.3.1 Metallurgy

The properties of steel are determined by its microstructure. This is influenced by the metallurgical composition, rolling technique and heat treatment. Modem steel rolling equipment allows detailed control of temperature and rolling pressure. The time history of pressure and temperature (together with the chemical composition of steels) determines the crystalline structure and thus its properties.

The microstructure of shipbuilding steels consists of iron-carbide *(cementite)* dispersed in a matrix *ofjerrite* (the metallographic name for one form of iron in steel). As the temperature of steel increases to a transformation temperature, the iron, which is in the ferrite phase, transforms to another form of iron *(austenite)* in which the cementite is highly soluble. Upon cooling below the transformation temperature, the austenite with dissolved cementite reverts back to ferrite and precipitated cementite. A laminated microstructure of cementite and ferrite, referred to as *pearlite*, is a major constituent of the common ship steels. In general, the carbon content and rate of cooling influence the microstructure, which in turn determines the strength and hardness of the resulting steel. Most hull structural steels are cooled in air after hot rolling or heat treatment. However, some high strength hull steels above 350 MPa yield strength are water quenched from above their transformation temperature and then tempered by heating to a temperature well below the transformation temperature. This quenching and tempering treatment produces a microstructure called *tempered martensite,* which is characterized by high strength and toughness.

In low carbon steels, in the absence of deoxidizers, the reaction of carbon with oxygen produces carbon monoxide during ingot solidification. The resulting ingot has an outer rim free of voids, and an inner zone containing voids derived from shrinkage and occluded gases. Such steels, which are identified as *rimmed steels,* are generally not used as hull steels in thickness over 13 mm, because of their relative low quality. *Semi-killed* steels, derived from ingots that are partially deoxidized, are better quality than rimmed steels and are commonly used as hull structural steels. *Killed* steels which are completely freed of the gassing reaction by additions of strong deoxidizing agents such as silicon or aluminum, are the best quality of the three steel types. Fine grain practice is the addition of elements such as aluminum, niobium, or vanadium to limit grain size during the period of grain formation. Steel quality may be further enhanced by subjecting the steel to a *normalizing* heat treatment, which homogenizes and refines the grain structure. Normalizing involves reheating steel to a temperature above its transformation range and cooling in air. Fine grain practice, fully killing and normalizing enhance steel quality.

20.3.2 Classification Society Steels •

Each ofthe individual classification societies have material specifications for structural steels which are intended to provide steels with adequate toughness without being excessively costly and which can be readily fabricated with shipyard equipment, processes and welding techniques. An attempt was made to unify material specifications in 1959 (3) and that effort continues today under the auspices of the International Association of Classification Societies (lACS).

Classification Society Rules (4) contain tables with the relationship of the various treatments to grade and thickness of hull steels and impact characteristics. Grades of higher strength steel are designated by a letter followed by a two-digit number indicating the yield strength in kp/mm^2, for example AH36 has a yield strength of 36 kp/mm^2 = 355 MPa.

Ordinary strength hull steels such as lACS Grades A, B, D, DS, CS and E are the most extensively used group of shipbuilding steels. The properties of these plain carbon steels depend on their chemical content and microstruct\)re. In addition to carbon, these steels contain manganese, silicon, phosphorus, and sulfur. Minor amounts of other elements may also be present. Higher strength steels with yield strengths up to 390 MPa, such as lACS grades AH, DH and EH are increasingly used. The higher working stresses permitted with these steels allow reducing section thickness and weight. A major difference between these steels and ordinary strength steels is that the higher strength steels have special additions such as aluminum, niobium, and vanadium, which promote microstructural improvements and strengthening. High strength low-alloy steels with yield strengths in the 415 MPa to 690 MPa yield strength range are occasionally used in marine applications. These steels utilize alloy additions and usually a quench and tempering heat treatment to achieve the specified strength level. A variety of toughness levels is provided by controlling the manganese to carbon ratio, requiring deoxidation, grain refining and heat treatments or, in some cases, by requiring impact testing of each plate or heat.

Profiles and bars are generally made to the same chemical composition and mechanical property requirements as the corresponding grade of plate steel. However, the most frequently used Grade A shape may have a slightly higher maximum carbon content (0.26% versus 0.23%), the manganese requirement is waived, and the upper limit of the tensile strength range is higher. These modifications make it compatible with those of the ASTM structural steel Grade A36, which is the most widely used and available industrial structural steel shape. In the case of cold flanging steel, requirements for tensile strength range and minimum yield point are reduced approximately 10% as compared to ordinary plates.

Heavy structural members of complicated shapes such as rudder parts, anchor bolsters, hawse transitions and propeller shafting supports are generally produced as *steel castings.* The grade of steel casting specified in the ABS Rules for Building and Classing Steel Vessels is substantially similar to the ASTM A27 Grade 60-30, which is readily weldable and has mechanical properties that approximate those of ordinary steel. Higher strength steel castings are usually purchased to the requirements of ASTM or other recognized commercial specifications. In designing large complex castings, it is often advisable to confer with foundry personnel to assure that the final design selected is compatible with the foundry techniques necessary to provide sound castings. It may be desirable to divide a large casting into simpler units to allow for optimum casting and then weld the units together. In spite of these precautions, castings are likely to be non-homogeneous. At the shipyard, cracks, sand inclusions, gas holes, and internal shrinkage may be revealed. The extent of repairs required in such cases must be determined by consideration of the service conditions and the location and extent of the non-homogeneous areas in each individual case. Because of their potent stress increasing effect, cracks should be excavated completely and the area repaired by welding. Rounded discontinuities caused by internal shrinkage, sand and gas holes are less objectionable in this respect, and complete excavation may be unnecessary when they occur in sections of low stress. However, these defects are likely to interfere with sound welding and weld NDT. If castings will be incorporated into the hull structure by welding, they should be examined closely and conditioned (repaired) in the welding areas. Prompt fabrication and inspection of castings upon receipt at the shipyard are necessary because of the time delay in procuring large castings. If the initial castings received prove to be unsuitable to the extent that repair welding is uneconomical, the time required for replacement may interfere seriously with building schedules. Steel castings used for critical applications, such as stern frames and rudder horns may be subjected to nondestructive test examination. The designer may have to require supplementary nondestructive tests for castings in critical welded assemblies to assure soundness in way of welded connections. To improve weldability and reduce residual stress, castings may be required to be subjected to a homogenizing annealing or normalizing heat treatment before welding or delivery.

Forgings are used for applications where the shape is comparatively simple (such as anchors and rudder stocks), but not sufficiently so for adaptation to a rolling process, and where there is a desire for better homogeneity than can be obtained in castings. While forgings are made in a wide variety of alloy steels of different mechanical\properties, those used for structural applications are usually of low-carbon steel (0.35 maximum), of welding quality, and with mechanical properties about the same as those of structural plates and shapes. Hull steel forgings are usually annealed or normalized and tempered to ABS or the comparable ASTM A668, Grade BH requirements. Large forgings are made directly from a cast ingot and unless a sufficient amount of work is done in forging to close and weld the porosity of the ingot, evidence of this condition may appear in the forging. ABS Rules require the forging to be less than one third the area of the ingot, except for large flanges, palms, and similar enlargements which may be not more than two thirds the area of the ingot. If the interior of these enlargements is exposed, as by machining, some of the ingot porosity may be evident. When this occurs, the condition must be evaluated as to its extent and the service condition for the section involved. Forgings are also likely to contain non-metallic inclusions, which are generally elongated in the direction of the forging and of relatively small cross section. Inclusions of moderate size and concentration are not particularly harmful. When encountered, inclusions should be evaluated by size, concentration, and location.

20.3.3 Further Relevant Specifications

Certain ASTM (American Society of Testing and Materials) grades of steel have been used as substitutes for lACS steels and to meet requirements for strength levels above those provided by the classification society steels. Steels with yield strengths from 350 MPa to 690 MPa have been found particularly advantageous for:

- container ships, where relatively small deck areas are available for the development of required hull girder strength,
- the legs of jack-up drilling units where the strength to weight ratio of the leg structure may be particularly important, and
- combatants, where their resistance to damage is needed.

In considering use of the high-strength steels, fabrication and cost trade offs and the proportion of increased strength that can effectively be utilized in the design should be taken into consideration.

There are a series of standards corresponding to the ASTM Standards (ISO-International), (BSI-British), (CSA-Canadian), (DIN-German), (NF-French), (JIS-Japanese). Ross (5) relates ASTM and foreign steel grades.

Military specifications cover steels analogous to those ofIACS and ASTM grades. In addition, expensive high-yield steels provide yield strength levels of 550 MPa to 900 MPa and provide superior fracture toughness. However, welding these higher strength steels require special precautions such as preheat, additional nondestructive testing, strict weld electrode control, as well as strict limitation of heat input and interpass temperature. Line heating is restricted, and forming and machining are more difficult and expensive. Degradation of material properties adjacent to the welds may offset the benefits of the higher yield in the base metal.

20.3.4 Ordered Material

The steel used in shipbuilding comes in plates or profiles. Plate dimensions differ from shipyard to shipyard. The maximum plate dimensions depend on external factors, for example railway limitations, and internal factors such as crane facilities, and plate storage. Thickness of plates is increased in steps of 0.5 mm. Actual plate dimensions follow from many aspects:

- maximum possible dimensions,
- volume sections,
- necessary steps in forming plates, and
- scrap, etc.

Typical dimensions for standard plates that may be kept in storage at a shipyard are:

- 8000 x 2400 x 5 6.5 mm, and
- 12 000 x 2700x7 12mm

Plates are delivered by steel manufacturers within margins of accuracy such as shown in Table 20.III. The plates can thus have considerable initial deformations.

Rolled or built profiles are used as stiffeners of plates in shipbuilding. The most popular profiles are Holland profiles (HP) following requirements such as EN 10067, angular profiles following national norms, and built profiles from flat steel welded using fillet welds. Profiles are ordered like plates following standard lengths or ordered to a certain application. Usually only one profile form (often Holland profiles) is kept on stock to simplify storage management and assembly plans. HP and L profiles are used for small and medium stiffeners, as they are cheaper than built profiles. L-profiles are less available in qualities required in shipbuilding and feature a stronger asymmetry making them more susceptible to fold over, but they offer more section modulus per mass (important e.g. for reefers). The relatively thin flange of the L-profiles allows easier longitudinal butt welds than for HP profiles. Built profiles from flat steel are employed for large stiffeners (longitudinal deck and bottom stiffeners in large ships, etc.) and in exact manufacturing.

Naval ships have traditionally used symmetrical profiles such as Tees.

20.3.5 Special Steels

The common structural steels are intended for the service normally encountered by most ships and marine structures. Special steels with enhanced properties are available where service conditions involve exposure to unusual temperatures, corrosion, or loading conditions. The use of special steel may be mandated by requirements of a regulatory agency or a design selection for improved serviceability.

Standard lACS grades can be applied as long as the service temperature lower limit is primarily related to the lowest possible sea temperature. Special *steels for low-temperature* applications are employed where extraordinary cooling effects exist for example in refrigeration ships and liquefied natural gas carriers. They may also be used where steel temperatures are not moderated by ocean temperatures, as in the case of upper structure of mobile offshore

TABLE 20.III Admissible Deviations from Ideal Plane for Standard Plates, Euronorm EN 29

Nominal Thickness mm	*Measured Length mm*	*Admissible deviation from plane for nominal plate width*							
		<1500	*≥1500 – <2000*	*≥2000 – <2500*	*≥2500 – <2750*	*≥2750 – <3000*	*≥3000 – <3250*	*≥3250 – <3500*	*≥3500 – <4000*
≥3 – <4	1000	7	8	10	—	—	—	—	—
	2000	14	18	22	—	—	—	—	—
≥4 – <6	1000	7	7	8	10	—	—	—	—
	2000	14	16	21	25	—	—	—	—
≥6 – <8	1000	7	7	8	8	8	—	—	—
	2000	14	14	16	17	20	—	—	—
≥8 – <10	1000	7	7	7	7	8	8	9	—
	2000	13	13	14	15	16	18	20	—
≥10 – <20	1000	7	7	7	7	7	8	8	9
	2000	12	12	12	13	13	16	18	20
≥20 – <50	1000	7	7	7	7	7	8	8	9
	2000	11	11	12	12	12	13	14	16
≥50	1000	Individually agreed							

drilling units (6). The special requirements associated with submersibles and related underwater systems have led to the promulgation of special rules for such service (7).

The major structural application of *corrosion resistant steels* in merchant ships is to provide a surface, which is resistant to chemical action from a liquid cargo. It is commonly used in the form of a 1.3 mm to 2.5 mm protective cladding on ordinary steel plates. However, it may be used in solid **form** for relatively thin plates and for shapes where the clad product is not available. In cases where cargo tanks are also used as ballast tanks, consideration should be given to the corrosive effects of both media. Welding of stainless steels can produce carbide precipitation in the *Heat Affected Zone* (HAZ), which in turn reduces corrosion resistance. Using steel with extra low carbon minimizes this adverse effect.

In some marine applications, such as the intersections of principal members of mobile offshore drilling units, loads are imposed perpendicular to the plate surfaces either as service loads, or by residual welding stresses.

The strength properties of rolled steel are not isotropic, but depend rather on the rolling direction. Conventional steels thus exhibit a much lower strength in perpendicular direction to the plate, which is evidenced by *laminar tearing,* Figure 20.5 (8,9).

Steels with improved through-thickness strength are provided by means of a variety of special melting practices; the degree of resistance achieved is dependent on the particular practice used.

Attempts have been made to use ultrasonic nondestructive testing to assure adequate through thickness properties. Such methods may be useful for those cases where weakness is due to gross plate laminations. They are not useful for cases where the weakness is related to metallurgical components in the microstructure.

The most common application for *abrasion reststant steels* is for components associated with the loading and unloading of bulk cargo. Two types of materials are available for abrasion resistance in such applications. The non-weldable type with high carbon, manganese, or chromium is not generally used for structural applications. The weldable type, similar to steels covered by ASTMA514, is available in the standard structural condition or quenched and tempered to high hardness levels for superior abrasion resistance. For special cases where localized wear is encountered, hard facing structural steel with local weld overlays may be considered (10).

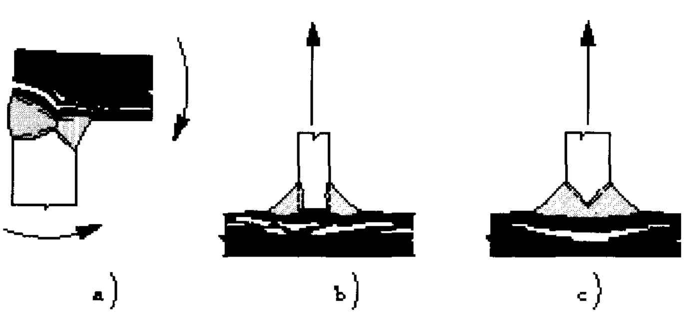

Figure 20.5 Laminar Tearing (8)

20.4 NONFERROUS ALLOYS

20.4.1 Aluminum Alloys

The advantages of aluminum alloys over steel are low density, high strength-to-weight ratio, and corrosion resistance in certain environments or retention of toughness at low temperature. Aluminum alloys are frequently used in superstructures, and for the entire hull structure of some ferries and small boats such as those serving the offshore industry. The low density of aluminum alloys makes them particularly attractive for applications where high strength-to-weight ratio.are of particular concern as in high-speed craft.

Since aluminum alloys increase in strength and maintain toughness as temperature decreases, they have proven particularly suitable for cryogenic services such as containment of liquefied natural gas. Aluminum alloys for plates, extrusions, forgings and castings are shown in Table 20.IV-A and Table 20.IV-B. Details of compositions, properties and methods of inspection are contained, for example, in the publications ofthe American National Standards Institute (ANSI) (1 I).

The most widely used alloys for marine structures are *non-heat-treatable* aluminum-magnesium alloys of the 5XXX series. Plates are normally mildly strain hardened (cold worked giving an *H* temper designation) to provide the desirable combination of strength and corrosion resistance. The 5454 alloy is used for applications where service temperatures above 65°C are anticipated. Higher strength forms of the 5XXX series, attained either by additional cold work (up to fully hard) or by magnesium contents over 5%, are not generally used, since they tend to exhibit an undesirable increased susceptibility to stress corrosion. Where special corrosion problems are anticipated, for example, in stagnant bilge areas, the alloys may be provided in special tempers (5083-H116, 5086-H117, 5454-H116), which are particularly resistant to exfoliation. Exfoliation is a form of intergranular corrosion, which produces delamination. Welding aluminum presents problems the designer must keep in mind. In general, the base plate in the vicinity of welds in non-heat treatable alloys, such as the 5XXX series, is trans-

TABLE 20.IV-A Mechanical Property Limits of Sheet and Plate Aluminum— Non-Heat-Treatable Alloys

Alloy and Temper	*Thickness (mm)*	*Ultimate Tensile Strength MPa* min.	*Ultimate Tensile Strength MPa* max.	*Minimum Yield Strength MPa* min.	*Minimum Yield Strength MPa* max.	*Minimum Elongation in 50 mm %*
5052-0	3.0–6.5	172	214	66	—	20
	6.6–75.0	172	214	66	—	18
5052-H32	3.0–6.5	214	262	159	—	9
	6.6–12.5	214	262	159	—	11
	12.6–51.0	214	262	159	—	12
5052-H34	3.0–6.5	234	283	179	—	7
	6.6–25.0	234	283	179	—	10
5052-H112	6.5–12.5	193	—	110	—	7
	12.6–51.0	172	—	66	—	12
	51.1–75.0	172	—	66	—	16
5083-0	1.5–38.0	276	352	124	200	16
	38.1–76.5	269	345	117	200	16
5083-H112	6.5–38.0	276	—	124	—	12
	38.1–76.5	269	—	117	—	12
5083-H116	4.5–38.0	303	386	214	296	12
5083-H117	38.1–76.5	283	386	200	296	12
5083-H323	1.5–3.0	310	372	234	303	8
	3.1–6.5	310	372	234	303	10
5083-H343	1.5–3.0	345	407	269	338	6
	3.1–6.5	345	407	269	338	8
5086-0	1.5–6.5	241	303	97	—	18
	6.6–51.0	241	303	97	—	16
5086-H112	4.5–12.5	248	—	124	—	8
	12.6–25.5	241	—	110	—	10
	25.6–51.0	241	—	9	—	14
	51.1–76.5	234	—	97	—	14
5086-H116 and H117	1.5–6.5	276	324	193	—	8
	6.6–51.0	276	324	193	—	12
5454-0	3.0–76.5	214	283	83	—	18
5454-H32	1.5–6.5	248	303	179	—	8
	6.6–51.0	248	303	179	—	12
5454-H34	4.0–6.5	269	324	200	—	7
	6.6–25.5	269	324	200	—	10
5454-H112	6.5–12.5	221	—	124	—	8
	12.6–51.0	214	—	83	—	11
	51.1–76.5	214	—	83	—	15
5456-0	1.5–38.0	290	365	131	207	16
	38.1–76.5	283	359	124	207	16
5456-H112	6.5–38.0	290	—	131	—	12
	38.1–76.5	283	—	124	—	12
5456-H116 and H117	4.5–15.5	317	407	228	317	12
	15.6–32.0	317	386	228	310	12
	32.1–38.0	303	386	214	296	12
	38.1–76.5	283	386	200	296	12
5456-H323	1.5–3.0	331	400	248	317	6
	3.1–6.5	331	400	248	317	8
5456-H343	1.5–1.0	365	434	283	352	6
	3.1–6.5	365	434	283	352	8

TABLE 20.IV-B Mechanical Property Limits of Sheet and Plate Aluminum—Heat-Treatable Alloys

Alloy and Temper	*Type*	*Thickness (mm)*	*Minimum Tensile Strength (mm)*	*Minimum Yield 0.2% Offset MPa*	*Minimum Elongation in 50 mm %*
6061-T4	Sheet	0.5–6.3	207	110	16
6061-T451	Plate	6.4–25.4	207	110	18
		25.4–76.2	207	110	16
6061-T6	Sheet	0.5–6.3	290	241	10
6061-T62 and T65	Plate	6.4–12.7	290	241	10
		12.7–25.4	290	241	9
		25.4–50.8	290	241	8
		50.8–76.2	290	241	6

formed to an annealed condition by the welding heat. The effect is to reduce tensile properties in the vicinity of the weld to the annealed or non-work hardened values.

Heat treatable aluminum alloys such as 6061-T6 develop strength by heating to an annealing temperature, water quenching and then reheating to a lower temperature to achieve a controlled precipitation of intermetallic compounds. The 6061-T6 alloy is occasionally used in marine service, particularly for extrusions, since it extrudes more readily than the 5083 or 5086 non-heat treatable alloys. The strength of the 6061-T6 alloy is higher than that of the 5083 or 5086 alloys; however, in the 6061-T6 alloy, the strength, ductility and corrosion resistance of the area in the vicinity of welds are severely degraded by the heat of welding limiting the applicability of the 6061 alloy for welded applications.

Aluminum alloys generally do not experience excessive *corrosion* under normal operating conditions. HlJVever, aluminum alloys are anodic to steel and most other metals, that is aluminum and steel with a galvanic solution (such as salt water) between the two materials will result in the aluminum *sacrificing.*

Such conditions may occur between faying surfaces of aluminum and other metals, between aluminum hulls and non-aluminum piping or when non-aluminum piping passes through aluminum bulkheads, decks, etc. In such cases, aluminum should be isolated from the other metal by means of suitable non-water absorbing insulating tapes or coatings or gaskets or by use of special pipe hangers or fittings. The 1974 SOLAS Convention contains certain stipulations on the use of aluminum. Aluminum in contact with wood, insulating materials or concrete should be protected against the corrosive effects of impurities in these materials by suitable coverings or coatings; concrete should be free of additives for cold weather pouring. Suitable precautions should be taken to avoid arrangements that could induce crevice corrosion in wet spaces, including particularly corrosion resistant material, sacrificial anodes or cathodic protection systems.

Compared with steel, aluminum alloys have relatively low melting points and tend to lose strength rapidly upon exposure to elevated temperatures. Aluminum does not *burn* in an exothermic reaction in the presence of flame. However, a fire in a compartment can heat the deck above, quickly weakening the deck sufficiently to let heavy objects fall through. In considering use of aluminum, due consideration should be given to applications where retention of structural integrity would be required in fire exposure. The use of appropriate insulation protection should be considered for such applications (12).

20.4.2 Copper-Nickel Alloys

Copper-nickel alloys have been used as solid plate to 10 mm thick, and as copper-nickel clad steel over 10 mm in thickness for small boats. The use of copper-nickel alloys for ship hulls due to their inherent antifouling properties was promoted in the 1970s with several demonstrator boats, but the ease and cost advantages of applying effective antifouling paints to steel hulls have rendered copper-nickel alloys as non-competitive for hulls. However, copper-nickel alloys are widely used in parts of the ship, which are in contact with seawater, but difficult to coat once installed, such as pipes, seawater coolers, etc.

20.4.3 Fiber Reinforced Plastics (FRP)

The main lightweight materials used in ships besides aluminum alloys are fiber-reinforced plastics (FRP), (13,14), (see Chapter 21 - Composites). FRP include the special case of glass-reinforced plastics (GRP). FRP is used both in single-skin and sandwich configurations. Current applications ofFRP in ships are mainly related to high-speed ferries, patrol and rescue craft, smaller navy vessels (e.g. mine countermeasure vessels), pleasure craft and sailing yachts. They are also increasingly popular in superstructures of cruise ships and larger naval ships, as well as secondary structures and components for all types of ships, from masts and casings to movable vehicle ramps and decks. In the main hull structure, FRP has been used for craft with length up to about 50 m. The advent of new, approved fire protection systems has made FRP also a viable and safe alternative to aluminum for ferry applications.

Advantages of FRP materials are [communication of Det Norske Veritas (DnV)]:

- good strength-to-weight ratio,
- readily formed into complex shapes,
- seawater resistant with little or no corrosion; the material is virtually maintenance-free, compensating high initial costs by low maintenance costs,
- stress concentrations are less critical than with metals, provided continuous fiber reinforcements are used. Hence fatigue cracking is less of a problem,
- low thermic conductivity; effects of fire can thus be more easily contained than with metal structures,
- non-magnetic (important for mine countermeasures) and transparent to electromagnetic waves (except when reinforced with carbon fibers). Carbon reinforced plastics can have good absorption properties with regard to electromagnetic waves, giving good stealth properties, and
- sensors can be readily integrated into FRP structures.

Disadvantages are: •

- high initial cost (except for mass produced items)
- need for adequate fire protection
- low elastic modulus (about III 0 that of steel) leading to relatively large deflections
- low through thickness strength.

Hulls and decks in FRP are often realized in sandwich structures. Additional advantages of FRP sandwich include very good flexural stiffness and strength for low weight, a high margin against catastrophic failure or penetration because of the two skins, additional buoyancy, good built-in thermal insulation, and the ability to build both large and small structures without costly moulds. Sandwich structures generally allow the lowest level of stiffeners to be dispensed with, giving smooth surfaces and a compact structure.

Details of the requirements are available in the form of classification society rules, for example, Det Norske Veritas (Dn V).

20.4.4 Concrete

Concrete consists of a mixture of stone aggregate bonded by a hardened cement. The aggregate consists of sand, gravel, and crushed stone. Specific gravity of concrete normally varies between 2.2 and 2.5, primarily depending upon the sizes and density in the stone mixture. The long-term durability of concrete in seawater has been well established (15). While concrete exposed to sulfate in soils or fresh water may react with the sulfate and degrade, seawater minimizes or prevents such deterioration. Where sulfate deterioration is of concern, special sulfate resistant concrete is used.

Ferrocement uses layers of steel mesh to reinforce concrete. The material has been used for making small boats up to 50 m with skin thickness of 10 mm to 40 mm in times of war, in third-world countries, (IS), and for amateur boat builders.

Reinforced concrete consists of cement reinforced by structural grade steel bars. It is usually used in thicknesses of 90 mm or greater. In compression, both concrete and steel are effective in providing the required compressive strength. However, cement provides no significant resistance to the tensile forces. Its application to ships therefore remains only of historical interest with concrete ships up to 7500 tdw being operated in World War II. Reinforced concrete has been more extensively used for very large offshore structures, which are floated into place, then ballasted down to sit on the bottom. With the advent of pre-stressed concrete, use of reinforced concrete diminished.

In *prestressed eoncrete*, high-strength reinforcing wires (up to 2070 MPa tensile strength), prestressed well in excess of 860 MPa, replace the structural grade bars used in reinforced concrete. The wires impose a high compressive load on the concrete. With the application of alternate cyclic loading, the force on the concrete will vary between higher and lower compression, but always remain in compression. Thus the threat of cracking of the concrete from tensile loading is eliminated. Concrete resists imposed shear and compression loads. Prestressed concrete develops several attractive properties as a result of its heterogeneous prestressed wire/cement structure. Loads imposed locally are dispersed through the structure via the numerous supporting metallic wires, thereby preventing or minimizing damage from concentrated shock loads, that is, the structure is highly resistant to fracture propagation. This and the relatively heavy thickness and large mass associated with prestressed concrete structures make the material an attractive candidate for applications where resistance to shock, collision damage or sudden failure is of concern. Prestressed concrete also has high damping properties, which are beneficial in minimizing vibration. Prestressed concrete has been applied to liquefied natural gas storage at -160°C. Brittle fracture of the reinforcing wires does not occur at cryogenic temperatures because of the thinness of the wire's cross section, and the supporting concrete matrix.

The relatively thick sections required of reinforced concrete and prestressed concrete structures as compared to **steel,** are obstacles to their use for many marine applications. However, concrete has been successfully used in fixed offshore structures and guides for such use are available.

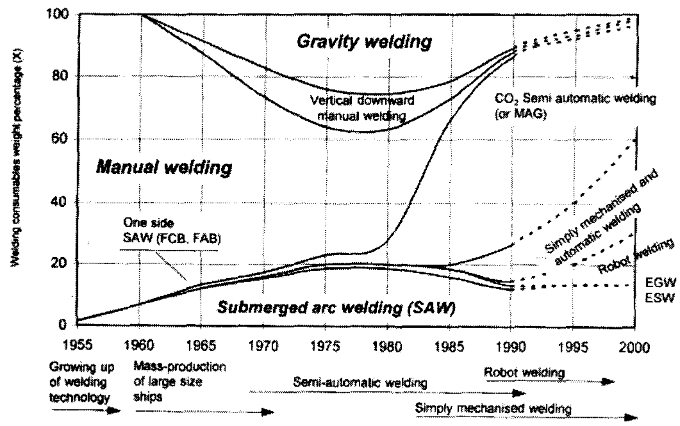

Figure 20.6 Development of Welding Methods in Shipbuilding (16)

20.5 WELDING

20.5.1 General

Welding continues to be the dominant technique to join ship structures. Over the decades, there has been a steady evolution from *manual* to mechanized to *automatic* and *robotic* welding (Figure 20.6) (16). Changes in welding processes have been driven by the quest to reduce production costs for reliable joints in structures. This includes all attempts to avoid costly post-processing and correction of unacceptable deviations and internal stresses due to welding distortion and shrinkage.

Welding is one of the major, if not the major single user of production man-hours for typical commercial ships. One source stated that it is 70% of the structural man-hours. As it is so important it is essential that the ship designer has a basic knowledge about welding. Its importance was recognized in the formation of a Welding Panel in the Natjmal Shipbuilding Program (NSRP) over 20 years ago and has resulted many publications. One of the more useful to ship designers is reference 17.

Hydrogen bearing compounds such as water or organic compounds present on the filler metal surface, in electrode coverings, or on base metal surfaces may dissociate in the welding arc to form atomic hydrogen. The atomic hydrogen penetrates and is highly soluble in molten steel weld metal and the zone of adjacent heat affected steel, which has been transformed to a phase known as *austenite.* The austenite forms when the HAZ of steel is heated above a critical temperature, (approximately 900°C for structural steels). As the solidified weld metal and austenitized HAZ cool to ambient temperatures, they are transformed into non-austenitic phases, which release most of the dissolved hydrogen from solution, since hydrogen is practically insoluble in these phases (Figure 20.7).

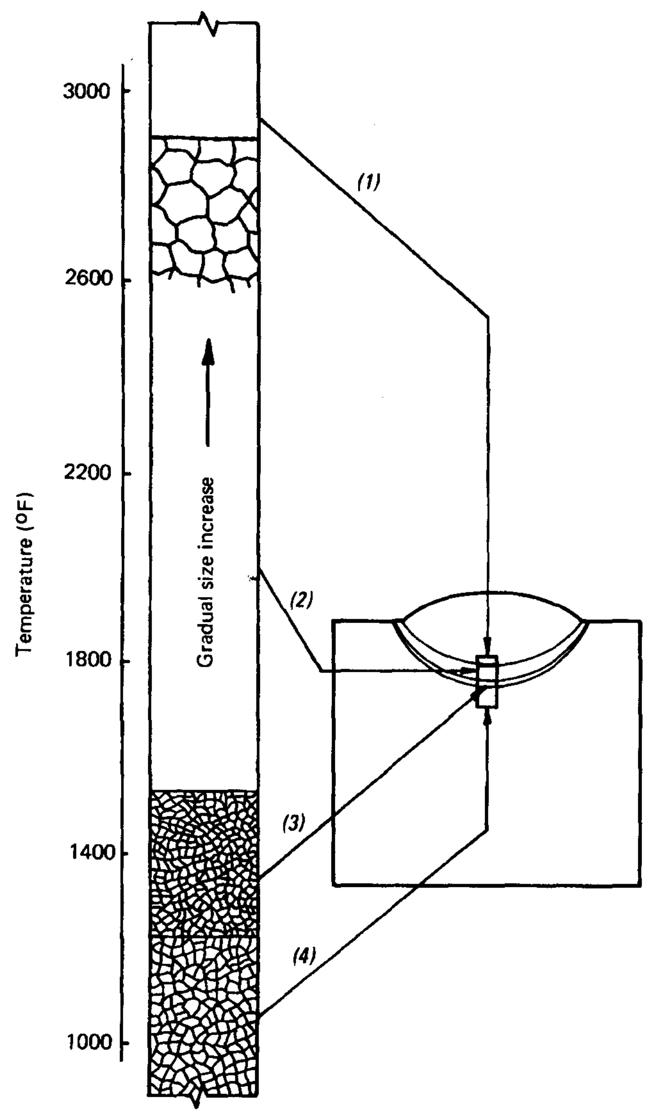

Figure 20.7 Effect of Welding Heat on Hardness and Microstructure of Arc-Welded Steel (18)

When hydrogen is released from solution in the presence of a hard zone in the microstructure and a high residual stress field, *hydrogen cracking* may occur. Since the time of such cracking varies from immediate to several days or weeks after the completion of welding, the phenomenon is also known as delayed cracking. The tendency for such cracking varies directly with the magnitude of hydrogen concentration, local metal hardness, and residual stress.

Ordinary strength shipbuilding steels are usually readily weldable with normal procedures. Because of the relatively low strength, and the absence of hardened areas in the HAZ, the tendency for hydrogen cracking under most conditions is minimal. However, for very thick or very cold work pieces, the accelerated quench rate would tend to produce a harder HAZ with increased residual stress levels; high residual stresses also occur in welds in highly restrained structures. Under such conditions consideration should be given to precautionary measures such as the use of low hydrogen welding processes (use of low hydrogen electrodes in shielded metal arc welding) and preheat to minimize adverse quench effects and reduce residual stresses. Preheat is usually not required for processes such as submerged arc or electroslag welding where the higher heat input rates and relatively large area heated in the weld vicinity provide conditions analogous to some degree of superimposed preheat.

When cracking occurs at elevated temperatures, the crack is usually intergranular (between grain boundaries). Such *hot cracking* is associated with excessive solidification and cooling stresses acting on constituents present at the grain boundaries, which are relatively weak at elevated temperatures. The weakened grain boundary may consist of specific low melting constituents such as sulfides in steel. In other cases the deposition of a weld bead of unfavorable geometry may impose excessive cooling stresses on the hot weld deposit, which has relatively low strength at ~evated temperature. For example, in submerged arc welding, weld beads such as those shown in Figure 20.8a, would tend to form a center section, which solidifies last and remains at an elevated temperature after the surrounding metal has solidified and cooled. The low strength at the grain boundaries of the material at elevated temperature is inadequate to resist the thermal stresses, and hot cracking occurs. Such cracking, can usually be readily prevented by changing weld parameters to produce a bead of more favorable contour (Figure 20.8b).

This will prevent hydrogen cracking by reducing possible hydrogen contamination from condensed moisture. As steel strength increases, sensitivity toward hydrogen induced cracking increases and the need for preheat and reduced moisture content (hydrogen source) of electrode coverings increases. Preheat tends to reduce weld and HAZ hardness and residual stress. Recommendations for selecting electrode types and preheat conditions for the various ship steels as well as other steels are available in th~ technicalliterature (19), and classification society rules.

The most widely used *stainless steels* in marine construction are readily weldable by inert gas metal arc, flux cored arc and shielded metal arc welding with standard techniques, using filler wires of compatible composition. Extra-low carbon varieties are generally recommended for welded construction. When such low carbon grades of base plate are to be welded, filler metals used should also be of extra low carbon grade.

Aluminum alloys used in marine construction are readily weldable with the inert gas arc welding processes, such as gas metal arc and gas tungsten arc (see subsection 20.5.3).

The gas metal arc process predominates because of its higher production speeds and greater economy. In welding aluminum, particular care should be taken to see that all surfaces in the way of welding are clean and free of contaminants, such as water stains, oxide films, and anodized layers. Preheat is not generally needed except when welding exceptionally thick sections, under conditions of high restraint, when humidity is very high, or when temperatures are below O°e. For the 5000 series alloys, prolonged preheating or exposure in the 65°C to 200°C range should be avoided, since it could sensitize the alloys to corrosion. Requirements and recommendations for welding in aluminum hull construction are contained in the rules of classification societies.

Welding of the 5000 series alloys, where strength is usually derived from work hardening, produces a zone within approximately 13 mm to 25 mm of the weld where yield and tensile strength of base metal are reduced to values ap-

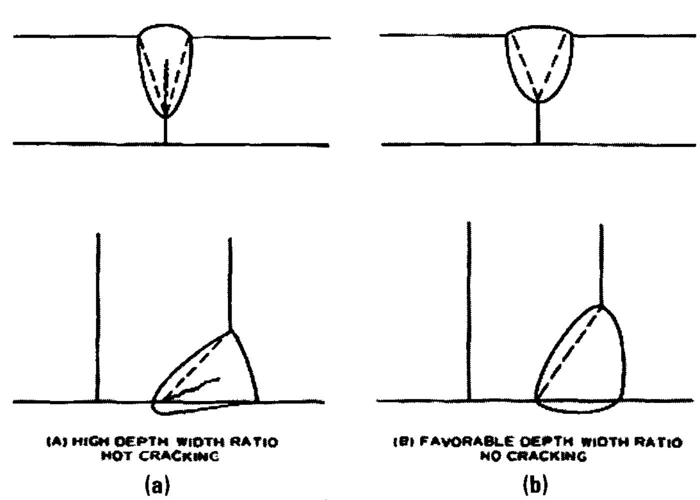

Figure 20.8 Effects of Weld Geometry (1)

proximating annealed base plate properties. This zone of reduced strength must be taken into account in design calculations. In the case of heat treatable alloys, tensile and yield strength as well as ductility and corrosion resistance are severely degraded.

The possibility of adverse effects resulting from galvanic corrosion should be considered whenever *dissimilar metals* are joined. The most common dissimilar metal combinations used in shipbuilding are stainless steel to carbon steel, and aluminum to carbon steel.

In welding stainless steel to carbon steel appropriate precautions should be taken to minimize harmful effects associated with dilution of the stainless steel by the carbon steel base metal. Excessive dilution can produce crack-sensitive weld metal near the carbon steel interface. When stainless steels are joined to carbon steel, nickel-rich stainless filler metals are generally recommended for any stainless steel weld layers, which come in contact with the carbon steel. When butt welding stainless clad steels, the carbon steel side is usually welded first with the appropriate carbon steel filler metal; particular care must be exercised to prevent the carbon steel weld deposit from impinging on the stainless steel overlay. The second side (stainless steel side) is then welded with a nickel-rich stainless steel filler wire. If the carbon steel layer is relatively thin, the entire weld may be made with the nickel-rich stainless steel filler. Similar procedures are used for welding other clad carbon steels, i.e. deposition of carbon steel filler metal on the cladding is avoided, and a filler metal that is compatible with the cladding and the underlying base metal is used.

Aluminum is not weldable to steel by conventional welding methods. An intermediate composite plate material consisting of aluminum and a steel layer or strip is used for welded joints between aluminum and steel. Speciallfanufacturing processes such as explosion bonding provide the bond between the aluminum and steel in the composite aluminum-steel plate. Each plate side is then welded to similar material. This type of connection has certain advantages in weather areas as regards corrosion compared to bolted or riveted connections. More recently, adhesive bonding has become an alternative to join dissimilar materials.

Selection of *welding filler metals* is based on the principle that the weld deposit should be comparable in properties to the base metal being joined. The filler metals applicable to the different grades of steels are specified by classification societies (20), and navies.

20.5.2 Welding Processes

Figure 20.9 shows the welding processes commonly used in shipyards, which will be discussed in more detail below. In semi-automatic processes, the electrode is manipulated manually and all other welding parameters including rate of electrode feed are controlled automatically. In automatic processes, all parameters including electrode manipulation are automatic.

Continuous improvement over the decades has ensured that arc welding in its various forms has remained the favored welding technology being well proven, robust and relatively inexpensive.

Shielded Metal Arc Welding (SMAW) is a process where heat is produced by an electric arc between a covered metal electrode and the work. The arc melts the metal of the electrode and the spray of droplets formed transfer across the arc to coalesce as a molten pool before solidifying as weld deposit. The formulation of the cellulose or mineral base types of electrode coverings assures that the covering will decompose or melt in the arc in an appropriate manner and rate, and accomplish the following:

- provide a gas or slag shield between the molten metal and the atmosphere during metal transfer and solidification,
- establish a favorable electrical environment for arc stability,
- provide a slag covering for the deposited molten weld metal which refines the metal and may, in some cases, provide alloying additions, and
- influence the fluidity of the molten weld metal, which in turn influences the shape and contour of the deposited weld bead. Since the covering has a great influence on the transfer and nature of the resulting weld deposit, coverings must be kept free of contaminants such as moisture or grease, which could alter their characteristics.

Manual SMAW ha's been increasingly replaced by semi-automatic methods like GMAW in modern shipbuilding.

Gas MetalArc Welding (GMAW) is an automatic or semi-automatic process in which a welding arc is formed between the work and bare electrode. The electrode is continuously fed from a spool, which may weigh up to 500 kg. A gas shields the arc and molten weld area from the atmosphere; such shielding is analogous in function to that of the covering in the SMAW welding. CO_2, 02' hydrogen, argon, helium, or a combination of gases is used for shielding. Combinations of gases allow combining the advantages of the different options. For steel welding, argon is usually always added to the active gases. The most common combinations of inert gases are often better known under their brand names like *Corgon, Krysal, Argomix,* or *Tycon.* GMAW is the most important welding technology of modern shipbuilding with applications to stainless steels, aluminum, other nonferrous alloys, and also low-alloy steels.

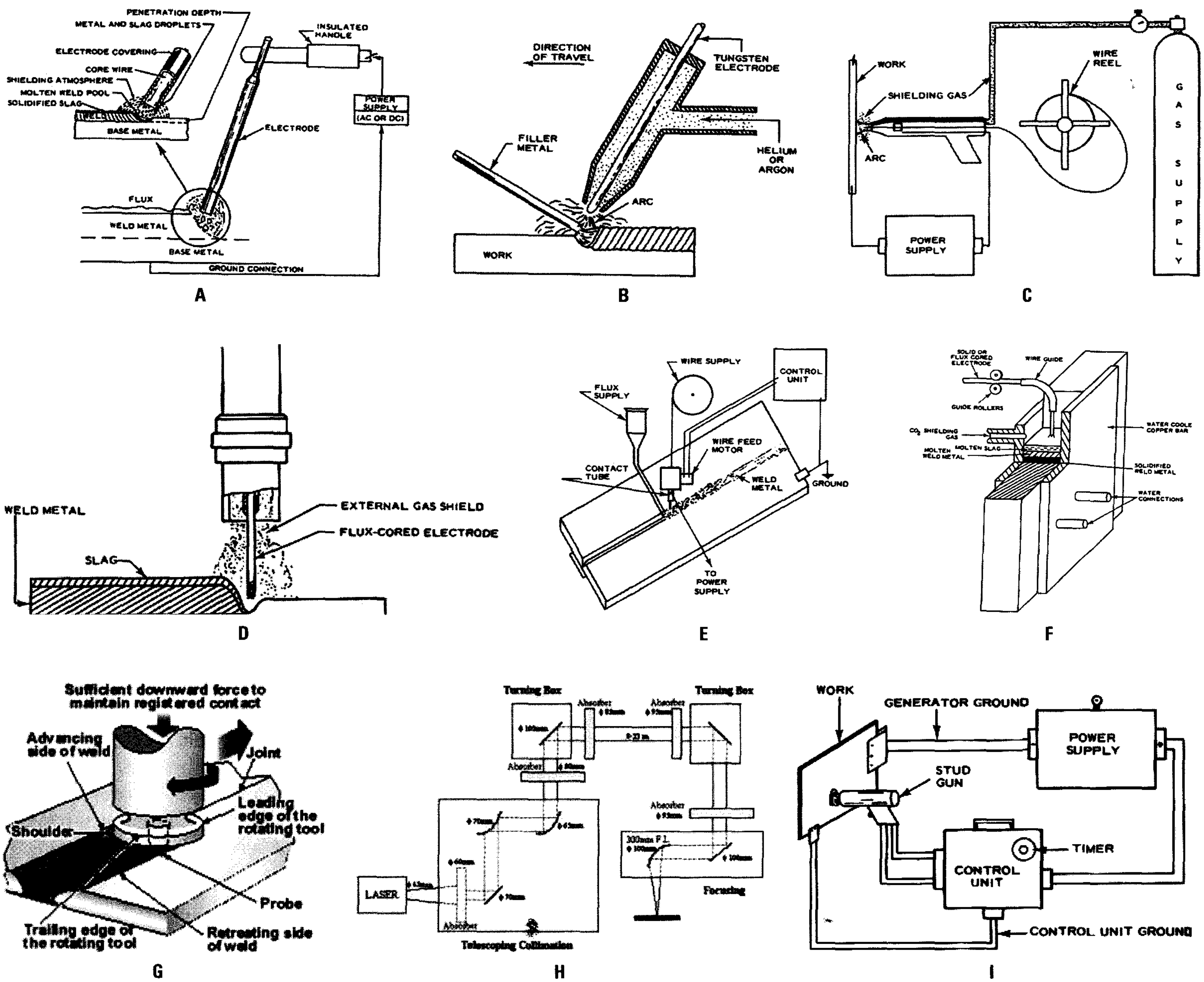

Figure 20.9 Shipbuilding Welding Processes (1,21) A) Sheiled Metal Arc Welding (SMAW). B) Gas Metal Arc Welding (GMAW). C) Gas Tungsen Arc Welding (GTAW) D) Flux Core Arc Welding (FCAW). E) Submerged Arc Welding (SAW). F) Electrogas Welding. G) Friction Stir Welding. H) Laser Welding I) Stud Welding

Submerged Arc Welding (SAW) is a semi-automatic or automatic process where an arc is maintained between a continuously fed spool (usually in wire form) and a work area. The welding zone is completely buried and shielded under a granular flux provided from an independent feed tube. The flux, when molten, maintains an electrical path of high current density, which generates a great quantity of heat. The insulating characteristics of the flux concentrate the heat in the weld area and induce significant melting of base metal as well as welding electrode. Under such conditions, high welding speeds (up to 27 kg/h), high deposition rates, significant melting of base metal, and deep weld penetration can be achieved. SAW with two- or three-wire electrodes instead of a single wire provides even higher welding speeds and deposition rates. SAW is frequently used for joining plates. Modem shipyards often make SAW welds with sound roots from one side only using a specialized one side butt welder, thereby eliminating the cost and time consumed in subassembly turning and re-welding the second side. This form of the process designated as one-side welding requires close control of joint fit, plate waviness, and weld parameters. Additionally, a special backing or tape on the back side of the joint is usually necessary to contain the molten weld metal at the root so that it forms a sound weld deposit of satisfactory contour. The drive for accurate manufacturing has motivated some modern shipyards to return again to two-sided welding which reduces distortion and shrinkage. Also some shipyards using one-sided welding have had to perform a lot of weld repair to the underside of the weld.

Electroslag Welding (ES) and *Electrogas Welding* (EW) are high-deposition rate processes analogous to SAW and GMAW respectively, except that the molten weld pool is contained within movable copper shoes at each side of the weld joint. A variation of ES uses a consumable guide tube instead of a permanent tube. Because of the exceptionally high deposition rates and large molten weld pools, arrangements are only available for vertical welding. In ES, a bar or strip is occasionally substituted for the one or more electrodes. Materials in excess of 400 mm may be welded in a single pass. ES allows also relatively high rates of welding speeds. Because of their relatively high heat input rates, ES and EW cause a greater degree of grain growth and other metallurgical changes in the weld HAZ than other processes, restricting the applicability of this technique.

Friction-stir Welding (FSW) is a relatively novel process, which relies on the friction between two metallic parts (or two parts and a metallic piece) to generate sufficient heat to soften the metal and provide ajoint (21). The process has been adapted to aluminum welding in shipbuilding. In FSW, a cylindrical shouldered tool with a profiled pin is rotated and slowly plunged into the joining area between two pieces of plate material, which are to be joined together. The parts have to be clamped to avoid them being forced apart during the process. Frictional heat between the wear-ref-stant welding tool and the work pieces softens the work pieces without reaching the melting point. The plasticized material is transported to the tool pin's trailing edge where it cools down leaving a solid phase bond between the two pieces. FSW can be used to join aluminum sheets without filler wires or shielding gas. High-integrity welds with low distortion can be achieved even in those aluminum alloys considered difficult to weld by conventional fusion-welding techniques. FSW has been employed for example for aluminum deckhouses on offshore platforms.

Laser Welding in shipbuilding started only in the late 1990s. In the laser beam welding process the laser beam focuses via welding optics *(mirrors)* on the surface of the work piece. After reaching the vaporization temperature, a steam capillary *(keyhole)* is formed in the work piece absorbing almost the complete energy of the laser beam. The metal steam flows away upwards, which allows the laser beam to penetrate deeply and thus vaporizes more material. This allows deep, narrow welds with practically parallel sides with small thermic loads and small HAZ even for relatively thick plates. For very narrow gaps and precise edge preparation, no additional weld material is needed. Alternatively, weld filler material may be added. Two types of laser can be used in ship construction applications, namely CO_2 laser and the Nd: YAG (neodymium-yttrium-aluminum-garnet) laser. The CO_2 laser has been available longer and delivers higher power. However, its higher wavelength only allows the beam to be delivered to the work piece via mirrors, which cause problems for larger distances. YAG lasers can be delivered using fiber optics, which greatly increases flexibility of delivery. Laser welding has been particularly popular for the manufacturing of sandwich panel structures for lightweight decks and similar structures. This application exploits the ability of the laser to perform a stake weld joining two elements by welding through them both.

Meyer Shipyard in Germany developed a hybrid laser technique, combining laser welding with GMAW to join prefabricated steel panels up to 6 m^2 in area and from 4 to 15 mm thick. The metal inert gas welder fuses filler metal to the seam edge of the panel, while the laser tracks behind it, melting through the seam root and penetrating deeply into the metal. The main advantage of the system is that the panels can be welded from only one side instead of from both sides simultaneously. The result is a significant savings in time and reduced use of welding material. The machine completes a 20 m weld in less than 10 minutes inducing very little distortion.

A disadvantage of laser welding is the relatively large brittleness of the narrow HAZ. By the early 2000s, plates up to 15 mm could be welded without major problems. Laser welding technology is still under development and typical structural designs in shipbuilding do not yet exploit the advantages of the new technology fully. European classification societies have passed *Guidelinesfor Laser Welding.*

In *Stud Welding* (SW) an arc is maintained between a stud or similar piece and the work, for a predetermined time so that both are properly heated. The stud is then brought to the work by spring pressure. A ceramic ferrule is sometimes used to provide partial shielding and some contour. The process is accomplished with an automated welding gun, power source, and control panel; the control panel regulates electrical parameters, welding arc time, arc distance, and the imposition of pressure between stud and work at the end of the welding cycle. The process is widely used in shipbuilding for attaching studs, clips, and hangers, insulation pins to structural members.

The use of different methods for a typical ship is shown in Figure 20.10.

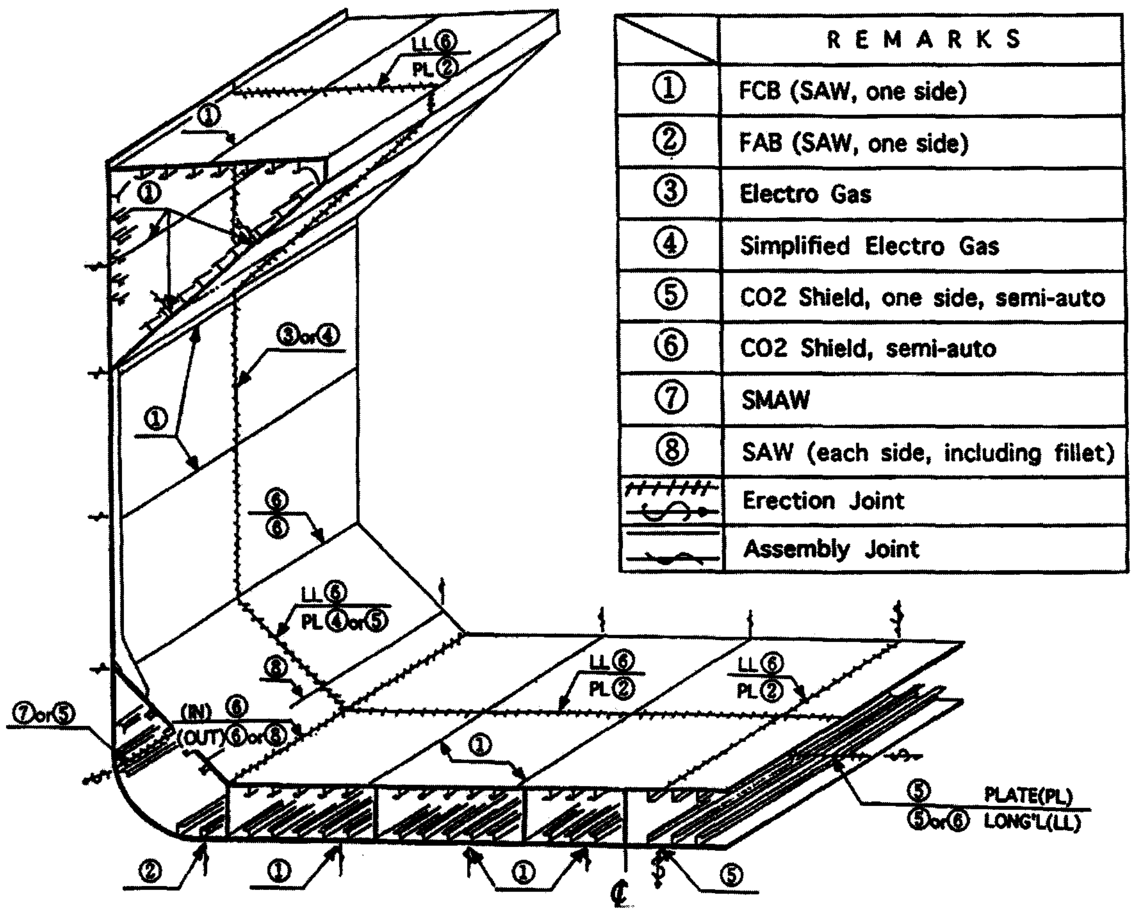

Figure 20.10 Typical Use of Welding Processes (16)

20.5.3 Design for Welding

Economy in ship construction and improvements in the serviceability and service life of ship structures can be enhanced if several principles basic to welded construcl.on are observed in the design process. These principles are derived both from service experience and from studies of the causes and prevention of structural failures in ships.

The mechanical toughness and corrosion properties of the *base metals* selected should resist excessive degradation from welding and forming practices.

This precaution is particularly applicable to materials with properties enhanced by heat treatment or cold work. When materials of widely differing corrosion resistant characteristics are joined, possible adverse galvanic corrosion effects should be considered:

- loss of toughness in the HAZ of some steels; particularly some higher strength steels, where weld procedures with excessively high heat input rates have been used,
- loss of strength, ductility, and corrosion resistance in the HAZ of the heat treatable aluminum alloys,
- accelerated corrosion attack on a carbon steel located adjacent to an area overlain with a stainless steel, and
- loss of ductility and toughness in materials subjected to excessive cold forming.

Hard spots appear in structural designs if structural members of considerably different stiffness are connected with fillet welds. This produces local stress concentration peaks associated with early fatigue crack initiation. Careful design reduces the danger of fatigue cracks considerably. Brackets should never end in a soft area (Figure 20.11). Stiffeners and profiles should not end abruptly (Figure 20.12).

The attainment of a sound *weld joint* and its proper inspection require appropriate clearances depending on the production weld process and inspection method. The provided access determines the degree and facility for weld automation and thus production cost.

Excessive welding may result in excessively high internal stresses, costs, and thermal distortion cost.

Since most conventional hull steels are not provided with minimum specified *through thickness properties,* they may

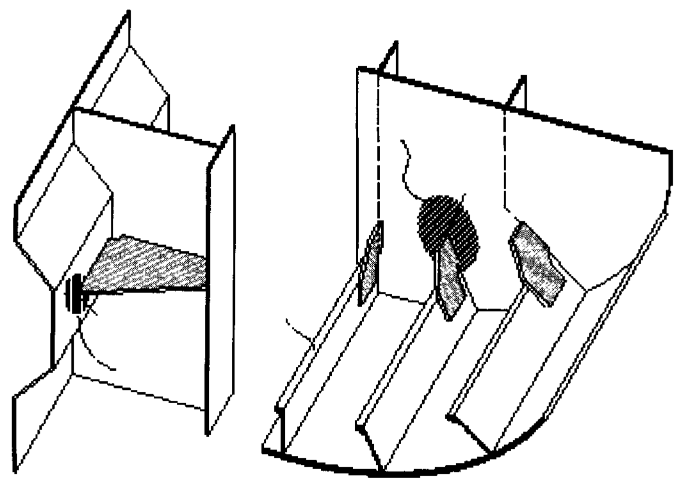

Figure 20.11 Brackets in Soft Fields (shaded) Creating Hard Spots [adapted from (8)]

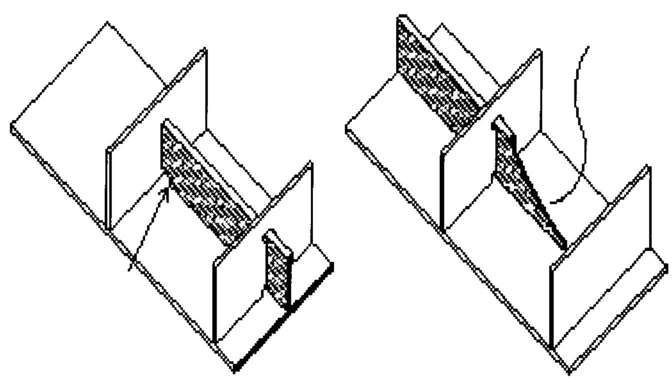

Figure 20.12 Profile Ends: Design with (left) and without (right) Hard Spots [adapted from (8)]

exhibit weakness under such a loading condition. Where through thickness loading in a structure cannot be avoided by a design modification, special materials with enhanced through thickness properties should be considered.

A standardized system of *symbols for welding and nondestructive testing* provides the designer with a means of communicating complete welding information on drawings (21) (Figures 20.13 to 20.16). In many cases, only a few of the elements of the symbol are required for a particular application. A similar system is also available for specifying nondestructive testing requirements. The requirement for details increases as the development of plans progress from the preliminary design to working plan stages.

Detail design plans, when used in the shipyard, should contain complete details of the welds and any nondestructive tests that may be required.

When plans form the basis of a contract, omission of any special requirements in respect to extent of penetration, finish, post weld nondestructive test examination etc. could lead to disputes between the purchaser and fabricator. When such details are omitted in final fabrication plans of the shipyard, such omission may allow for inadequately penetrated, finished or inspected welds.

20.5.5 Qualification Tests

Weld procedure qualification tests determine whether the welding process and procedure will produce welds of satisfactory soundness and properties. Procedures may be qualified on the basis of proven satisfactory use for similar work under similar conditions. In other cases, formal procedure qualification tests are required by classification societies. Where an approved filler metal is not used, additional all weld-metal tensile and Charpy V-notch tests may be required to establish the adequacy of weld deposit properties. Depending upon the application and the process; all weld-metal tension, Charpy V-notch impact, macro-etch, and hardness tests may be required for special high-strength or low temperature steels or for certain processes, for example, ES welding.

Welder qualification or performance tests determine whether an individual welder has the required skill to make satisfactory welds. Welders are generally qualified on the basis of their ability to fabricate welds, with the procedures, welding positions and general type of base metals of concern, that will either satisfactorily pass guided bend tests or alternatively exhibit satisfactory soundness upon radiographic examination. Additional welder qualification tests may be required if there is a change of welding process, change of welding pdSition, or doubt relative to the ability of the welder. In the case of automatic welds, the ability of the machine operator may be determined. In the interests of economy and convenience many regulatory agencies have similar qualification requirements, and in most cases each may accept the qualifications of the other.

In addition to the above, *production welds* may be subjected to nondestructive tests or sampled and tested for mechanical properties. Such a requirement may be imposed for certain applications such as welding for some low-temperature service applications.

Supplementary to the mechanical weld tests, appropriate *production control* tests verify that the conditions, materials, and procedures of qualification tests are maintained during production. Visual examination determines the quality of prefabrication fits, and final weld appearance and sizes. As required, weld soundness may be verified by nondestructive evaluation.

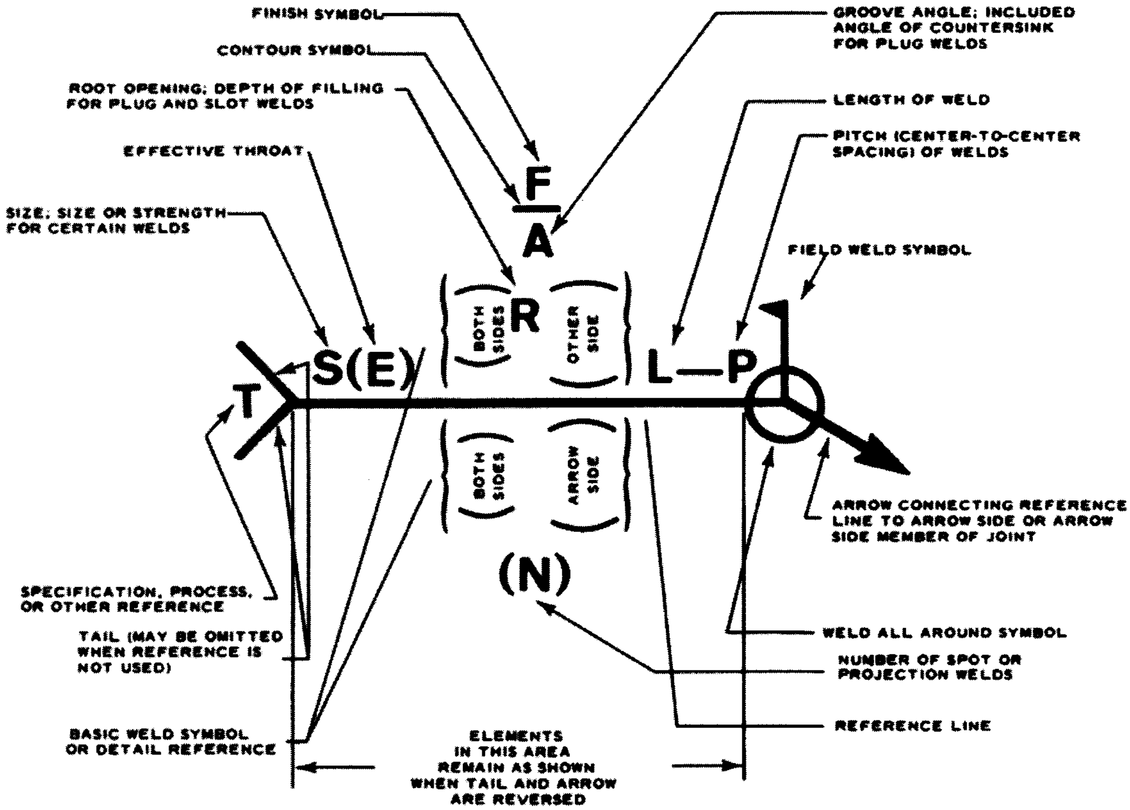

Figure 20.13 Generalized Welding Symbols (1)

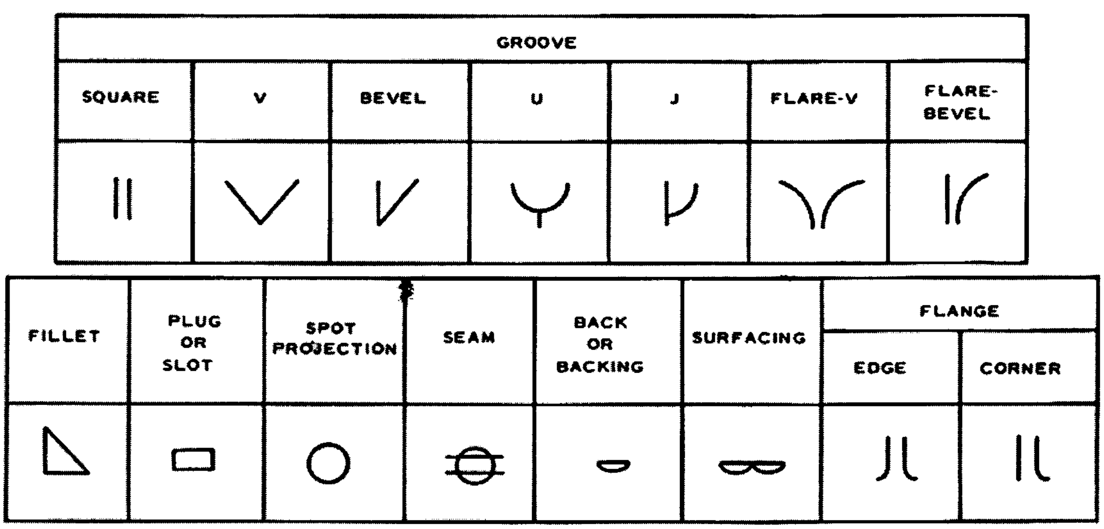

Figure 20.14 Basic Weld Symbols (1)

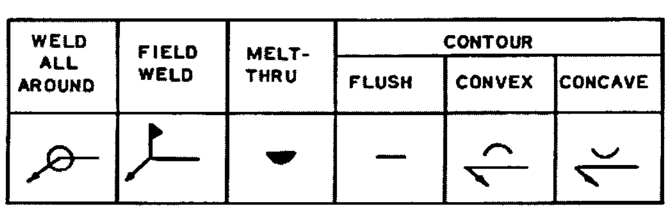

Figure 20.15 Supplementary Symbols (1)

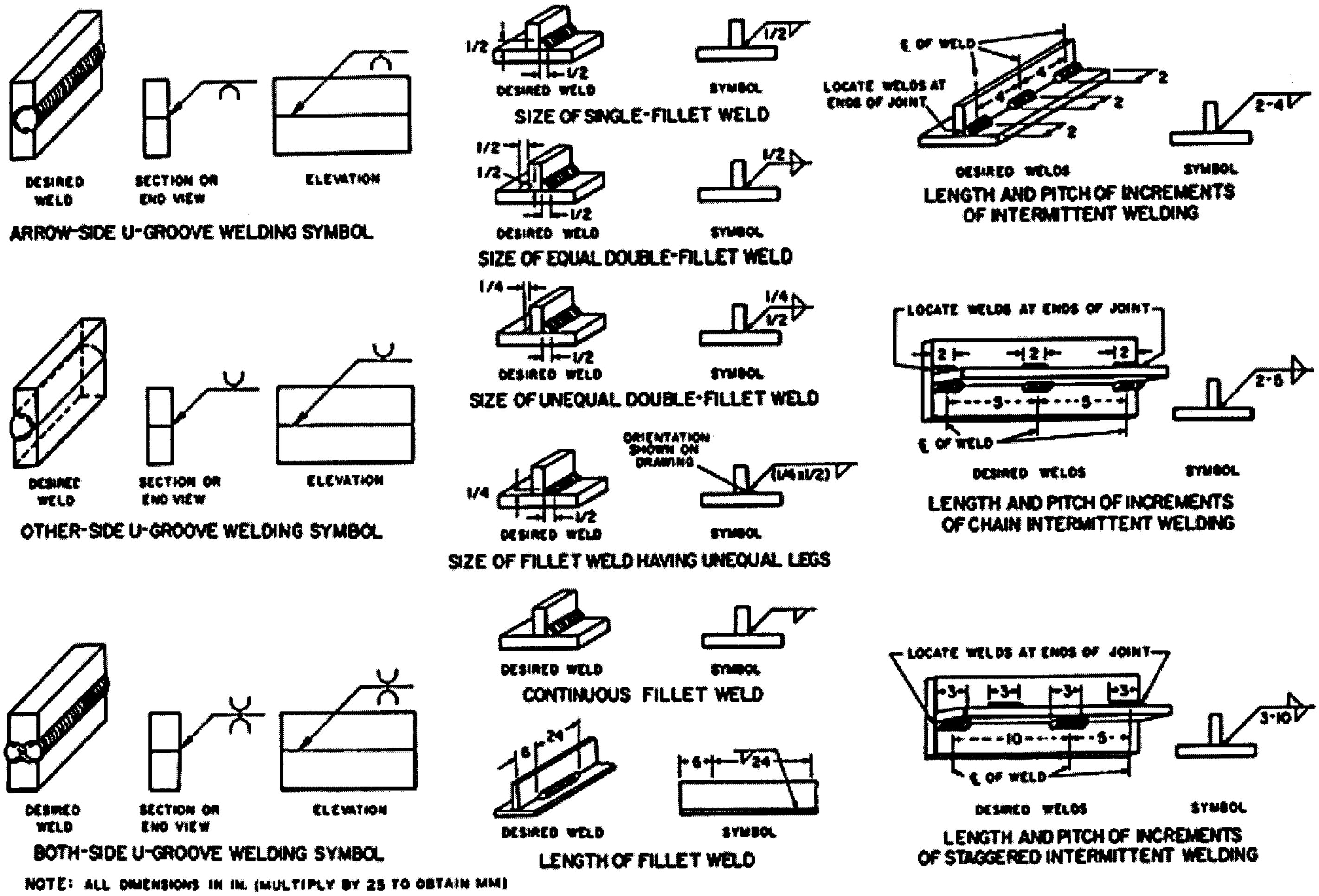

Figure 20.14 Basic Weld Symbols (1)

20.5.6 Nondestructive Evaluation

Nondestructive evaluation is widely used in shipbuildi!g to assess the soundness of welds during construction and repair. A nondestructive testing schedule is frequently required for new designs or where new or unusual service requirements are anticipated. It may also be included in drawings where the designer desires to achieve increased structural reliability by specifying a greater extent of nondestructive testing.

All welds are subjected to *Visual Inspection,* ranging from the casual inspection of the welder to a formal inspection by a qualified weld inspector or ship surveyor. Visual inspection, when properly accomplished, is considered by many to be one of the most important methods of quality assurance, since it provides important information not readily available from other methods. Visual inspection of the weld joint prior to welding will prevent welding injoints, which have been improperly cleaned, prepared, or fitted. Completed welds are eJ£amined for surface soundness, regularity, geometry, and alignment. Promptly reported deficiencies allow timely correction of production operations.

Magnetic Particle Inspection magnetizes the base metal (steel plate) by passing a superimposed electrical current through. Then finely divided magnetic particles are applied to the plate surface. A flaw at or near the surface will form a pair of magnetic poles, which will attract the particles. The technique is highly directional in sensitivity. **It** is most sensitive to flaws approximately parallel to the direction of the imposed current and practically insensitive to flaws perpendicular to current direction. Magnetic particle inspection is used in shipbuilding to verify the soundness of root passes, intermediate weld passes, back-gouged areas as well as completed welds and to inspect large steel castings and forgings. **It** is most widely used for the inspection of fillet welds, since such welds are not ordinarily subjected to ultrasonic or radiographic inspection.

Dye Penetrant Inspection uses a liquid penetrant of low surface tension to penetrate surface cracks. After excess penetrant is removed from the surface, a suitable developer is applied which draws the liquid penetrant from the crack and holds the wetted developer; the remainder of developer is freely released from the area. The indication will appear as an accumulation of developer around the crack or fissure and, depending on the system used, may be white, colored or fluorescent under ultraviolet light. Dye penetrant systems are used for surface inspection of non-magnetic materials such as non-ferrous alloys (aluminum) and corrosion resistant steels. They may also be used for inspection of steels in lieu of magnetic particle inspection.

Radiographic Inspection is used for the examination for internal soundness of welds, castings, and forgings. This method employs x-rays or gamma rays capable of penetrating the thickness of material under investigation; a suitable film records the amount and pattern of radiation transmitted. Discontinuities in the material such as cracks, porosity, lack of fusion, as well as areas containing low density material (such as entrapped slag) will present less of a barrier to the radiation; the greater amount of radiation through such sites will be indicated by denser (darker) areas on the film negative. Entrapped materials higher in density than base metal (such as tungsten in aluminum welds) will appear as less dense (lighter) areas. Some of the more important factors to be taken into account in radiographic examinations include:

Safety: Both x-rays and gamma rays present potential hazards to the operator and to other personnel working in the area of exposure. In addition, special precautions and regulations are applicable to the storage, handling, and disposal of the radioisotope used as a gamma ray source.

Selection of Appropriate Source: The penetratinl characteristics of the radiation source selected must be appropriate for the density and thickness of the material being examined. The sensitivity of the procedure is decreased substantially if the penetrating characteristics are excessive or insufficient.

Radiographic Technique: The penetrameter, which consists of a series of holes in strips of various thickness or a series of wires of graded diameters, is superimposed on the work during exposure and is indicated as a set of graded images on the final film. It provides a permanent indication of the sensitivity of the inspection.

Interpretation of Indications: The interpretation of the results involves subjective judgments for which appropriate training and experience are required. This facet of the inspection is particularly difficult in borderline cases of acceptability where disagreements between recognized experts are not unusual.

Radiographic inspection of ships is carried oufmainly in important locations such as intersections of butts and seams in sheer strakes, bilge strakes, deck stringer and keel plates, and butts in and about hatch comers in main decks, and in the vicinity of breaks in superstructures. In other marine structures, it is mainly carried out in highly stressed areas, and at butt and seam intersections. Complete (100%) radiography is usually used only in specialized cases such as for liquefied gas containment or the shell of a submersible.

Ultrasonic Inspection is used as an alternative to radiography for the examination of welds, castings and forgings; it is also used to measure thickness and detect laminations in plate. An ultrasonic impulse generated by a crystal is transmitted at a prescribed angle through the material being inspected; the impulse continues until it reaches a surface from which it is reflected back to the crystal. Any discontinuity in the path of the impulse will also act as a signal reflector; the size, orientation, and geometry of the discontinuity will determine the proportion of impulse reflected back to the crystal. For base metal examination the beam is usually transmitted perpendicular to the plate surface (compression or longitudinal wave technique) and for weld examination, angles of 4SO to 70° are used (shear wave technique). As in radiography, use of qualified personnel and procedures is essential. One of the limitations of ultrasonic inspection is that it is highly dependent upon the skill and interpretations of the technician, and errors relative to improper transmissions of sound impulse or interpretation of the signals received cannot usually be reviewed. In addition, permanent records of the sensitivity attained or of the indication, analogous to those of the penetrameter and actual discontinuity indication in a radiograph are not usually provided. However, the convenience and economy of inspection offered, as well as its greater sensitivity to important linear discontinuities such as cracks, make it an attractive alternative to radiography.

Rules for all nondestructive techniques for inspection of ship hulls as well as pertinent references relative to qualification of operators, equipment, techniques, and acceptance standards are issued by appropriate regulatory agencies, classification societies, and technical societies such as ASNT (American Society of Nondestructive Testing) and ASTM.

In some cases a given weld will be found to meet the applicable hull inspection standard for one method and not meet the applicable standard of the other. In such cases, unless there are specific stipulations, the results of the inspection procedure selected as the primary inspection method usually governs, unless the indications revealed by the supplemental method are shown to represent a significant threat to the integrity of the structure.

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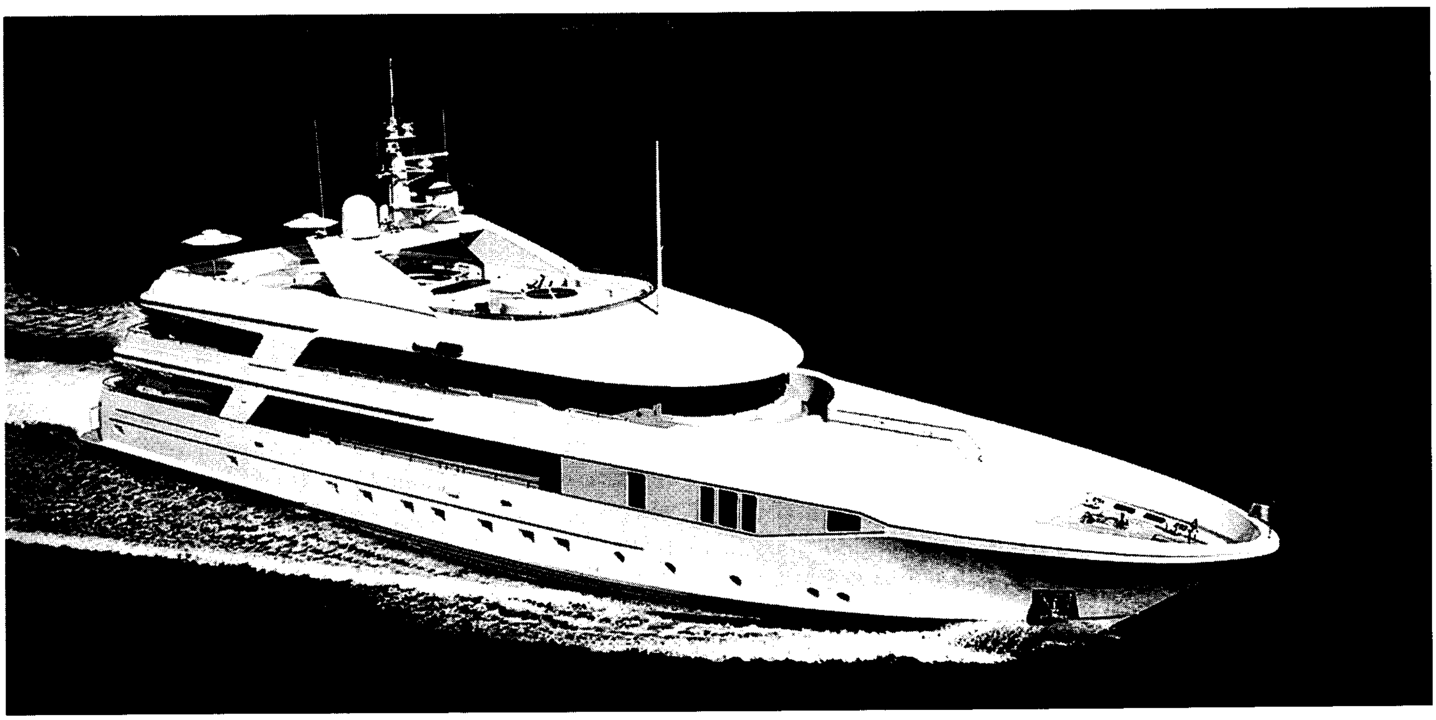

Figure 21.1 49 m LOA Motor Yacht

Chapter 21

Composites

Albert W Horsman, Jr.

21.1 NOMENCLATURE

ASTM	American Society for Testing and Materials
CFRP	Carbon Fiber Reinforced Plastic
FRP	Fiber Reinforced Plastic
GRP	Glass Reinforced Plastic
HAP	Hazardous Air Pollutants
PVC	Polyvinyl Chloride
SAN	Styrene Acrylo-Nitrile
VOC	Volatile Organic Compounds

21.2 INTRODUCTION

Composites are two or more distinctly different II1ferials combined into (but not dissolved into) one structure to perform a function neither material is capable of doing independently. Steel reinforced concrete is a composite material, but not one normally considered for marine use. However, ferro-cement yachts, powerboats and barges have been built in limited numbers with a certain level of success. Metal matrix composites use small amounts of very high strength fibers, such as boron, in a metal matrix, such as steel or aluminum. However, these composite types are not common to applications found in marine use.

For common marine industry use, composites are mostly E-glass reinforcements in a thermoset plastic polymer matrix, usually polyester or vinyl ester resin. Kevlar or carbon fibers are used more recently as specialized reinforcements, and epoxy is used more as a matrix. Fiber Reinforced Plastic (FRP) is a common referring term. Glass Reinforced Plastic (GRP) was a frequently used term but is out of date because of more common use of Kevlar and carbon reinforcements. *Fiberglass* or just *glass* is still used to refer to the same group of materials. With many different types and fabric weave arrangements for the common fibers, many formulations of the basic resin types, and vastly different properties achieved from various fabrication methods, even the seemingly narrow field of marine composites includes an almost infinite choice of materials.

Many books have been written on the subject of composites. Quite a few universities offer full courses of study in the subject through the doctoral level. Countless short courses, conferences, symposia, and trade shows are devoted to composites. Therefore, only a brief introduction to the materials, their usage, design, and manufacture, will be presented in this chapter.

21.2.1 Short History

Composites have been used in marine structures since just after World War II. Scott (1) and Greene (2) cover more of the early developments. As each established publication gets dated, the technology advances. Developments and advances in composite materials and structures, as measured by market share, are growing at 6%-10% a year, whereas steel and aluminum usage is fairly constant.

The motor yacht shown in Figure 21.1 is over 47 m LOA, with a fiberglass hull and deckhouse, and is fully deserving of listing in a book on *ship* production. This vessel is fully self-sufficient and is classed for open ocean voyages. Twenty years ago a vessel of this size was on the ship side of the scale. Now that composite vessels are this large, they are often still considered *boats.*

Marine composites have been used for limited applications on large steel ships, both in combatant and commercial types. FRP is used on submarines for flooded nose fairings, diving planes and non-pressure hull decks. A weapons enclosure prototype (3) has been developed for use on a destroyer. A similar size composite director room room was designed, built and tested for U.S. Aegis class destroyers (4). The U.S. Navy *Osprey* class 57m coastal mine hunters (MHCs) are all-composite structures as are many European minehunters. A composite mast is being used on the new amphibious ships. Even the older U.S. Navy wood mine countermeasure vesselsare sheathed in FRP, have numerous FRP extrusions for rails, ladders and other minor attachments, and have their entire stacks of FRP.

Due to fire protection regulations, use of composites on commercial passenger vessels in the U.S. has been limited to small passenger carrying no more than 149 passengers. Larger FRP passenger vessels are in service abroad. The Swedish have built the 72 m VISBY class corvette of carbon fiber reinforced plastics (CFRP).

Most lifeboats on ships are FRP (see Chapter 16 - Safety).

FRP hatch covers are used on dry cargo barges for inland transportation but are not used on ocean-going vessels. Pre-formed FRP deck gratings are used on raised catwalks on oil tankers, offshore platforms and aircraft carriers. Composite pilings have proven to be stronger than the wood ones they replace (5). However, widespread use of composites on ocean-going commercial vessels has not yet occurred.

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21.3 BASIC MATERIALS

Most ship production books, references, and research are based on steel construction, most of which is transferable to aluminum. Composites are a bit different, so some digression for a brief look at material properties is in order. Manufacturing aspects are discussed in Section 21.5.

21.3.1 Reinforcing Fibers

The most commonly used composite reinforcements in the marine industry are E-glass fibers, with aramid or carbon fibers used for local reinforcement or special applications. Table 21.1 shows the raw fiber properties of some of these materials. Table 2-4 in Greene (2) has more data on the fibers. Note that these are just fiber strengths. The as-laminated composite strengths are much less by 50 to 85%. After the materials are woven or stitched into a fabric and combined with resin, the actual properties of the finished laminate vary drastically and are quite dependent·on the method of fabrication.

Table 21.II is a comparison of some of the basic properties for various fabrics laminated with different fabrication methods and different resins. One would expect the unidirectional polyester resin laminate to be much stronger than the WR polyester laminate, but the glass content referenced (6) is *approximate* and the possible differences in structural qualities of different grades of polyester resins can be significant. However, the superiority of a vinyl ester resin laminate with 70% glass content can be seen.

Conversely, poorly prepared (low glass content-high resin content) laminates can have poor physical properties. Note in Table 21.II how the properties ofthe laminated unidirectional fabrics compare to the raw fiber properties in Table 21.1.

Instead of going into great detail here, interested readers are referred to the readings from Scott and Greene (1,2). The two references cover the subjects fairly well, and additional information is available in the references of those two books. However, a brief introduction to the materials is in order.

E-glass fibers, the most common reinforcing material, go from filaments to strands to rovings. For mat, continuous rovings are cut back to either continuous or chopped strands. Different weight rovings are woven, bonded and stitched into a wide variety of fabrics. The listing in Appendix A of Greene (2) is just a sampling of the different types available. Going deeper into the reference material, even more types will be found. Woven roving at 800 *gmlm*^{2} alternating with layers of 450 *gmlm*^{2} mat was *the* common construction material, and is still in fairly common use.

This combination is often referred to as *a pair.* Even designers and builders familiar with high strength materials refer to *two pairs* to define alternating layers of mat and woven roving of these weights. If strength was needed in an off axis direction, the normally 0/90 woven roving could be laid at that angle. However, production boat builders can pay just a bit more for a combination material, with the mat already bonded to the woven roving, and save the labor of cutting and bonding in an extra layer of mat. This material is often designated a 2415, with an 800 *gmlm*^{2} woven roving bound to 450 *gmlm*^{2} with a soluble binder.

Standard woven roving is an inexpensive roll fabric, but because of the weave pattern, the full strength of the glass fibers is not able to develop. Each of the rovings is woven over and under those fibers in the opposite direction. Thus the rovings are in a wavy pattern and cannot be pulled quite straight and tight. But that is only in tensile and compres-

TABLE 21.I Reinforcement Fiber Properties

Fiber	*Tensile Strength MPa*	*Tensile Modulus GPa*	*Ultimate Elongation*	*Cost U.S.$/KG*
E-glass	3450	72	4.8%	1.70 to 2.60
S-glass	4600	87	5.7%	13
Kevlar®	3600	124	2.9%	57
Spectra® 900	2600	117	3.5%	50
Carbon	2400 to 4800	230 to 390	0.38 to 2.0%	20 to 80

TABLE 21.II Laminate Properties

Laminate	*Tensile Strength mPa*	*Tensile Modulus GPa*	*Compressive Strength mPa*	*Flexural Strength mPa*	*Interlaminar Shear Strength mPa*
Wet Layup 800 gm/m^2 WR E-glass 50% Poly	323	22	270	360	23
Wet Layup 800 gm/m^2 0/90 Biax E-glass 50% Poly	241	15	255	448	—
SCRIMP 800 gm/m^2 70% Poly WR	464	31	290	461	31
SCRIMP 800 gm/m^2 70% V.E. WR	489	32	473	620	50
Wet Layup 450 gm/m^2 Mat–30% Poly	86	8	156	164	—
Wet Layup–900 gm/m^2 Uni E-glass 50% Poly	508	24	304	754	—
Wet Layup–300 gm/m^2 Uni Carbon 58% Epoxy	1607	130	315	1197	—
Wet Layup–400 gm/m^2 Double Bias (+/–45) w/ 250 gm/m^2 mat E-glass 45% Poly	126	9	151	216	—

50% = 50% glass content by weight, POLY=Polyester resin, V.E. = Vinyl Ester resin, WR is Woven Roving, SCRIMP™ = Seemann Composites Resin Infusion Molding Process

sive loading. If the laminate experiences out of plane loading, perpendicular to the surface, flexural stiffness is usually desired and the woven roving develops thickness and stiffness faster at a lower cost. Woven fabrics are also available in different weaves that can reduce some of the strength development problems.

However, as long as production efficiency is considered, the use of even heavier material is possible. One builder using the SCRIMP method (Seemann Composites Resin Infusion Molding Process, which is discussed in Subsection 21.5.2.5) on a 16m or so sailboat uses a stitched fabric heavy enough to do both skins of a sandwich in one layer. This is a 580808 fabric, with four 490 gm/m^2 unidirectional layers stitched together on each of the four major axes (1960 gm/m^2 total), with a layer of 225 gm/m^2 mat bound on each side. This material would be very difficult to laminate by hand or even to get through an impregnator.

Mat is usually thought of as a necessary element between the layers of woven roving or unidirectional to increase interlaminar adhesion. However, a number of builders have produced large boats of woven roving in multiple layers without mat between the woven roving. The interlaminar shear strength may not be the best, but it is quite adequate as failures are unheard of in these hulls. If the layers are compacted tight enough in the lamination process, usually resulting in high glass content, the successive layers of glass start to lay in between each other in an effect known as *bundling,* and the interlaminar strength is increased. Various lamination processes that give better bundling and higher fiber content are discussed in Subsection 21.4.1.

At the other end of the scale, it seems that the cost of carbon would be prohibitive for a large vessel, but in Sweden they found that the comparative cost disadvantage of carbon was offset by the use of much less material for the structure in their 72 m naval vessels. Their weight, performance, and cost optimization routine showed lower cost as they increased the amount of carbon in the structure. However, this is a naval vessel with extreme performance requirements, and the structural needs justify the use of carbon reinforcement. Boats of ordinary size and performance, built of properly oriented E-glass, can be quite adequate.

The driving force in laminate selection is to specify the laminate that meets the requirements for the structure and the conditions of strength, weight, cost, production method, and the builder's and owne"s preferences. The possible combinations of fabric, resin and lamination process are nearly endless.

21.3.2 Resin

The choice of resins seems as endless as the choic't0f reinforcements. As with reinforcements, choices are based on cost and performance. Scott (1) and Greene (2) cover the basics very well. Many of the problems in the manufacturing side of boat production come from improper handling or use of resins. Among those are:

Improper catalyzation: The catalyst for poly and vinyl ester resins is a very small percentage (1.5% to 3.0%) in relation to the resin and must be thoroughly mixed. Poor catalyzation results in improper cure, poor physical properties and potential blister formation. In hot weather, some laminators cut back on the catalyst too much to give more working time.

Shelf life: Resins and catalysts are reactive polymers, some more than others, and can degrade over time. They must be stored in a relatively cool place and kept sealed until ready for use.

Excessive exotherm: Most resins are cured by chemical reaction generated heat. A high catalyst ratio for the weather conditions, or building up laminate thickness too quickly, can cause excessive exotherm which in turn causes shrinkage in the laminate, gives poor physical properties, and can damage molds.

Moisture: Most standard resins are sensitive to moisture. Special formulations are needed for high humidity areas or shop humidity must be controlled.

To demonstrate the consideration of resin variables, a hypothetical exchange between a builder (B) and a resin supplier (S), typical of a builder's decision process on resin selection follows:

B: I want an inexpensive resin that does the job,

S: ortho(phthalic) polyesters are inexpensive,

B: But ortho's are brittle and have low blister resistance,

S: epoxies are strong but flexible,

B: but I'm not building an expensive race boat, just an ordinary 19m cruising yacht,

S: nothing is (or should be) ordinary about a $2 million boat,

B: but the competition sells boats for the same price with polyester resin, but then I need a cost-effective combination of resins to give me the performance I need in selected locations.

Cost and quality conscious builders will likely use a vinyl ester skin coat to make a good permeation barrier, an iso polyester as the main structural resin to give better physical properties, and go back to the vinyl ester for better secondary bonds. They can use a sandwich laminate and build a quieter, lighter boat that is naturally insulated so it will use less resin anyway, thus relegating resin cost to a secondary consideration.

This is a typical scenario that leads to the use of a vinyl ester skin coatJiso polyester combination, a very popular and viable choice of resins for this size boat. Larger and higher performance yachts might use all vinyl ester laminates, or more advanced production techniques that produce higher strength laminates but use less of the high priced resins. Smaller vessels, which are trailered or stored on lifts more often, and are not usually built in sandwich, can probably get by with the lower performing, less expensive resins.

21.3.3 Specialized Resins and Putties

Resins can be blended and filled to give a number of features required beyond normal fabrication. Some of these features include:

- fairing,
- liner bonding,
- strake filling,
- core bonding,
- gap filling, and
- hull-to-deck joint bonding.

These putties can be formulated for mixing by hand or, for higher volume and proquction applications, pumping from drums through guns.

21.3.4 Core Materials

Core materials used for boats come basically in two forms: foam and balsa. There are a number of other materials in the references that are considered as core materials, but first it is necessary to go through the steps of defining the required attributes for a core material; then these other materials can be categorized better.

21.3.4.1 Sandwich functions

The primary purpose of a low density core material is to separate the FRP laminate skins so that the resultant sandwich composite has better out-of-plane stiffness with less weight than a monolithic built up laminate. Most people in the industry refer to single skin (many built up layers of laminate) as *solid* construction. However, that infers that the sandwich construction is something other than solid. More often than not, the sandwich is more solid than the single skin. The term *monolithic* is more fitting.

The core carries shear loads and some compressive stresses. As always, cost is a consideration. Both the material cost and the installation cost must be considered. Scott (1) lists some other desirable attributes as: t

- good shear strength,
- rigidity,
- good bonding surfaces,
- light weight,
- survivability in the marine environment, and
- sufficient crushing strength (compressive strength).

Shear strength used to be the only major physical factor considered in deciding core selection, in widely accepted classification society and engineering texts. The higher the shear strength, the less core material one needed in a sandwich panel. Balsa was the obvious choice to satisfy that requirement, plus it was a lot less expensive. However, some early sandwich vessels were built with long grain balsa, and a small leak or crack in a laminate would quickly expose a lot of balsa to the water, which would get into the balsa and initiate rot and water-logged hulls.

Balsa is now supplied in end grain form for boats. This gives very good rigidity, much better bonding surfaces, and is still light and inexpensive.

However, a balsa-cored laminate needs to be very stiff in relation to the expected loads because it has a lower strain to failure and can fail when severely overloaded. All of the primary marine core materials behave well in normal loading conditions. The resistance to overloads and ability to absorb energy is related to a core's shear elongation. This information is not provided in earlier referenced books, so some basic data on shear elongation is provided in Table 21.II!.

It turns out that the relative cost of the cores is similar, but not directly related to the shear elongation. Therefore, the issue of survivability becomes important because each core's shear elongation is closely related to the damage tolerance when a sandwich is loaded beyond the expected or normal loads.

Following is a description of core material physical performance criteria from Karl Brandl, who some like to call the father of foam sandwich construction as extracted from an out of print book (7) produced by Airex in 1973:

> The main function of the core material is to distribute local loads and stresses over large areas. Local stresses applied to one side of the sandwich have only a reduced local effect because of the exposed skin and the core will distribute the loads to a larger area of the sandwich. Because of this fact, a sandwich structure generally exhibits superior behavior under bending, torsion, impact and compression, parallel or perpendicular to the skins. Beside its function of a spacer and connecting unit between the skins, a core material for boat building must therefore exhibit enough resilience to absorb impact stresses. Its ability to cushion and absorb shocks in alternating stresses and torsion loads, passing from skin into the core, as they occur in a boat under practical conditions, is a necessary requirement of the core. Such dynamic stresses as well as impacts due to

TABLE 21.III Core Shear Elongation

Core Type	*Shear Elongation (%)*
Balsa	5
Cross-linked PVC	15–20
Ductile cross-linked PVC	45
Linear SAN	55
Linear PVC	80

the lack of resilience of the core can result in severe damage and eventual destruction of the entire structure. A boat or ship should, with all required stability and homogenous stiffness, not be an inflexible structure.

It should be a mechanically stabilized structure, which still allows movements within the elastic range of its materials. It should further exhibit the characteristic to withstand short term overloading without destruction and lasting damage.

Generally, one can encounter unexpected loads and stresses by two alternatives. One is to design to such a limit that the structure will in every case be many times stronger than the unexpected loads, i.e., the structure would have to be over-designed (above the usual factor of safety).

A more advanced engineering concept is to counter the unexpected loads by a structure, which, having sufficient mechanical strength and stiffness, is still in a position to withstand peak loads without damage of serious consequences to the structure. In order to realize this concept, a rigid elastic structure is a prerequisite design criterion.

Apart from the lightweight, the latter is a more professional and probably a more economical approach. The basic concept of the sandwich principle in the boat building industry rests on the aforementioned premises.

So there it is, be absolutely stiff enough to handle all the oads, both normal and overloads, or be stiff enough to hanlle the normal loads, and resilient, damage tolerant, and trong enough to handle the overloads without failure.

21.3.4.2 Not regular marine cores

A number of materials are listed in Greene (2) in the same context as core materials, but the author prefers to consider them in a different category because they fail ~me of the basic requirements for a regular marine struc1:ural core material.

Honeycombs are quite light and very stiff, but the open cell structure invites water migration over time, even without any skin damage. The water vapor molecule is very small and can penetrate the relatively thin-skinned sandwich hull structures, even with some of the best epoxy resins.

This is not to say honeycombs cannot be used in the marine environment. America's Cup racing yachts use honeycomb hulls, but they are pulled out of the water after every use and are not air conditioned, so the conditions for water vapor migration are not present. A number of the honeycombs, including paper, coated papers, aluminum and plastic, are good for interior floors, bulkheads and nonstructural parts (8), but these specialties will not be considered in this chapter.

Plywood is often listed as a core material, but it fails the lightweight criteria. Plywood is often used as *a high-density insert* for handling high local loads in an otherwise low density cored sandwich. Transoms in outboard powered boats are a popular use of plywood. But plywood is about 600 kg/m^2 and a high-density core that can take high local loads is around 200 kg/m^2. Plywood is less expensive, but one must be careful to seal the exposed surfaces to avoid water exposure and rot. Newer treated plywoods mostly prevent the degradation. It is also more difficult to bond to smooth surfaced plywood.

Laminate bulking materials are used in a similar fashion to core materials, and in relatively flat panels they behave, and must be designed, similar to the mainstream cores, but they are not thick enough and light enough to be used as mainstream sandwich materials for large marine panels. These also are used as *print blockers,* an extra layer of material that prevents the heavier fabrics under a smooth, gelcoated surface from printing when the resin post cures. Use of proper resins and cure cycles can prevent printing also.

Sprayed-in *core materials,* basically falling into the filled resin or putty category, can be useful for small highly shaped sections that need some stiffening. However, at 600-700 kg/m^3, they rather fail the lightweight test. Used conservatively where needed they can be a useful tool.

The processing and operating temperature of a cored laminate can be a limitation. Some vessels have dark colored decks that can soak up a lot of solar heat in the tropics. This heat can be enough to reduce the physicals of some of the foam and plastic honeycomb cores. Structural performance in the heat of a fire is also a concern in some applications. This is one area where balsa really works well.

Performance of a hull in the water is often not the limiting factor; survivability of a thin-skinned sandwich on a few blocks in a boatyard, Q.f on the rollers of a trailer, can be a more critical design load. High ambient temperatures, such as found when a boat on a trailer is sitting on a hot, dark asphalt-paved parking lot, can compound this problem. Proper trailer design details that avoid this situation are necessary.

21.3.4.3 Core bonding

Core bonding used to be done with a layer of mat soaked in resin. This method is still used with some success, but has a couple of drawbacks. Resin can drain from vertical surfaces, leaving those cored areas starved for enough resin to affect a proper bond. Some of the plastic foam cores are very sensitive to styrene migration, so the normally styrene-rich resin in a thin bond line can lead to styrene migration problems. Mat and resin cannot fill irregularities between the laminate and the cores, so gaps may be left in the bond line.

Most of the major core suppliers offer bonding putties that do a much better job of ensuring the critical bond between the skin and the core. Some of the core bonding compounds require the use of a *priming* resin applied directly to the core before it is placed into the putty, which is applied to the FRP skin. Properly catalyzed to cure in a thin bond line at the same time as the putty, a strong bond is effected.

Some of the desired features of this bonding layer are:

- the putty can *hang* on a vertical surface,
- putties can fill and bridge gaps in laminate overlaps and comers,
- putties can rise to fill gaps and kerfs in the core,
- for the most part they have a better adhesive bond to the already cured FRP part,
- for the most part they have a lower exotherm when curing to keep from post curing, shrinking and causing print-through of the outer skin, and
- most can be used for hand lay-up or vacuum bagging (preferred) the core into the laminate.

Some builders manufacture their own putties from filled laminating resins, but the performance features fall short of the specialized bonding compounds from the core suppliers, who use specialized resins and fillers to achieve the desired properties. These are for the poly and vinyl ester resins. Epoxy is a bit easier to formulate into a workable putty.

The number of choices of cores, and limitations on core selections increases the number of variables in the composite design problem. It does make it quite interesting and gives a number of options to use to create the right structure for the intended loads, overloads, and the desired performance criteria.

The use of core materials, problems with them, and heated debate on how best to design sandwich panels, has been carried on in *Professional Boatbuilder* magazine (i-l 0) particularly over the last few years.

21.4 DESIGN

21.4.1 laminate Properties

Scott (1) describes in great detail the orthotropic nature of mat and woven roving laminates. Alternate layers of woven roving material at +/- 45° could be used to even out the humps in the directional strength chart in Scott's Figure 10, to try to achieve a more isotropic laminate, but there may be problems with large lumps when the laminate overlaps bunch up.

Keep in mind these *orthotropic* properties are only in-plane properties. Out-of-plane properties are quite different and somewhat less. There are special 3D knitted fabrics that have a large number of strands *sewn* through the plane of another 2D fabric to achieve the desired strength. It is very difficult to get composites to exhibit the quasi-isotropic behavior of metals, but that is a big advantage of composites. The fibers (most of them) can be oriented in the direction of stress. Symmetry usually is not needed, and is rarely achieved in standard marine laminates.

The charts of different properties in various directions from Scott (1) illustrate the variability seen in most all areas of composites. Even though all of these data are all based on the mat/woven roving laminates, the same variability is exhibited in knitted biaxial materials, unidirectional materials, and combination materials. Those considerations also apply to the properties in Appendix A in Greene (2). Also consider that Appendix A is mostly based on a 50% glass content. The glass content achieved by different manufacturing methods varies from 30% to 70% as listed in Table 21.IY.

With this basic knowledge and good references, a reasonable estimate can be made of the strength of a mixed laminate. A designer is not always given a choice of materials, just as with metal boats. For example, if the potential owner wants a steel boat for a city park canal boat that needs 4 mm steel, and gets 5 mm steel donated, the designer must rework weight, balance and weld details to suit. If someone gets a great deal on 6061- T6 aluminum plate for a boat hull, even though the as-welded ultimate tensile strength is 50% less than original, that sets the design parameters.

Similar material decisions are made with composites. Choices for fabrics and resins often are made by economics and timing, not necessarily engineering.

Mixed laminates come from builders who prefer to use certain materials (or can get excess from a distributor) and let the engineer determine how much is needed.

Or, some builders and/or designers have certain preferences for material stacks, such as laminates listed in Table 21.Y.

This particular builder wanted a little bulk and balance

TABLE 21.IV Glass Content

Lamination Method	*Glass Content by Weight*
Low Quality Hand Lay-up	30%
Good Quality Hand Lay-up	40%
Lower Quality Impregnator, Wet Bag, SCRIMP, VARTM	50%
Higher Quality Impregnator and Wet Bag, SCRIMP, VARTM	60%
Autoclave	70%

TABLE 21.V Typical Laminate Schedule

Hull Bottom	*Weight gm/m²*	*Thickness mm*	
Paint	450	0.5	
Cloth 340	567	0.43	
EBX 600	1000	0.81	
EB 600	1000	0.81	Outer Skin
EB 600	1000	0.81	2.86 mm
Priming Resin	950	0	Core t
A550 Core-Cell	2515	25	25 mm
EB 600	1000	0.81	
EB 600	1000	0.81	Inner Skin
EBX 600	1000	0.81	2.43 mm
	10 482	30.79	
+5% skin overlaps	10 880		
		= 10.9	kg/m²

TABLE 21.VI Flexural Modulus

Item	*Flexural Modulus-GPa*	*Weight Fraction*	*Multiple GPa*
225gm mat	5.5	.273	1.5
2 X 600/225	11.7	.373	4.4
KB 440/225	13.8	.159	2.2
540/225	13.1	.191	2.5
Sum			**1[illegible]6**

in the laminate. The fabrics are commonly available and the laminate exceeds the classification society requirements for this size and type of craft. The topsides were a simple reduction of this schedule by dropping an EB 600 from each skin. The *as laminated* weights are indicative of stitched uni-directional fabrics wet bagged in epoxy.

One program used for sandwich panel analysis needs the flexural modulus of the laminate, estimated as shown in Table 21.VI for a mixed layer laminate. This estimate is not totally accurate as it is the reinforcement fraction that should be used in the calculation, but it is conservative and the results are close to the actual testing for this type of construction.

21.4.2 Test Methods

Greene (2) gives a good explanation of the various test methods and what mechanical laminate property is actually being determined. Table 21.VII gives examples of problems that are related to test methods.

The *hydromat* test jig was developed separately to test marine panels. It is shown in Greene (2), Figure 3-87 on page 180. The hydromat test has been developed into ASTM D6416. In some cases, it returns results similar to 3-point bend tests, but it gives more reliable results for a wider range of large marine panels subject to lateral loads.

With sandwich composites, the laminates and cores are tested, both separately and together. Core testing brings it's own set of problems. For example, making a compressive test sample square instead of round can give lower results for some cores. The rate of testing can be varied within the parameters of the test methods, but some cores are strain rate sensitive and show different results at different rates. The SNAME HS-9 Paftel is addressing these problems and others, but progress is slow.

TABLE 21.VII Test Method Problems

Problem	*Solution*
Samples are fairly small, boats are big.	Use larger samples, adapt the test method, and consider the hydromat panel test.
Samples are often made up in a lab on a table. Boats are built out in a shop in hot, dusty conditions.	Take the sample from a cutout on a boat, or make the sample in the shop alongside the boat.
A sample, cut 5% off axis from a panel, will result in a 15% reduced strength for some tests.	Cut carefully; larger samples reduce considerably the source of errors.
Testing usually returns an average value; most design criteria call for some minimum value.	Know the statistical spread on the test results. Adjust the safety factor to account for the unknowns.

Concise, repeatable material properties that show up consistently in the tests should not be expected. However, as stated in the references, and in ABS and other classification society guides, testing is necessary to support the design, prove the capability of the builder and confirm assumptions.

Testing is also a form of quality control, buteven better if used as process verification. If testing is used as quality control, it normally will be done too long after the lamination. Then it is too late to change a laminate or laminating process when it is shown to have low physical properties. If the process is verified by testing under conditions similar to those in the shop before lamination begins, then small sample tests can be used to verify that the larger part will actually be built as expected.

21.4.3 Local Loads

Local loads on a boat are basically the pressure loads from the vessel pushing through or bouncing over the waves. These can be static head pressures, impact slamming pressures or hydrodynamic pressure. The vessel must be designed to handle the worst case of these loads. For a planing vessel that has a speed to length ratio greater than 9, the full impact pressure should be applied to the whole bottom area because the boat can become airborne and slam down on any part of the bottom. (The speed/length ratio is the speed in knots divided by the square root of the waterline length in meters). For a pleasure yacht, this is rarely the case and impact pressures need only be applied to the forward parts of the vessel. Scott (1) has a full explanation of all the likely local load cases.

21.4.4 Concentrated Loads

Some concentrated loads also are considered in the loc!1 load set. Special local loads that must be accounted for are trailer bunks or rollers, davit bases, mast mounts, stays, chain plates, etc. For thin-skinned sandwich panels, local compression inserts and additional laminate are usually needed to handle these loads.

21.4.5 Global Loads

The global loads on a composite hull must be considered a bit differently because of the low modulus of the commonly used E-glass material. Generally, for a normally proportioned vessel under 30 m LWL, hull bending is not critical and the local pressure loads are the most critical loading case. One exception is in the case of burying the bow in large waves, the foredeck captures a big compressive load, and the design needs to account for that.

For vessels over 30 m, longitudinal bending in waves must be considered. Even with low modulus E-glass laminates, this is usually not much of a problem up to 55m hull~. Past that length special consideration needs to be given to the design.

The ABS Guide (14) has reasonable design criteria for the various aspects of composite vessels, as do most of the other classification societies. Variations in safety factors and loading criteria are responsible for the differences between the rules and guides. However, as hull length approaches 50 m, hull girder stiffness must be studied carefully. Discontinuities in main deck structure due to stair towers, steps in decks, routing the stiffening structure around other obstacles, etc., can combine to reduce hull girder stiffness.

Racking loads also must be considered, carefully especially in low modulus composite vessels. Usually bulkheads, and well-placed web frames or ring frames, will handle these loads. Transferring this structure through continuous decks to support and hold the deckhouse in place requires special details that are in keeping with the manufacturing process and sequencing.

21.4.6 Connections to Non-composite Structure

In a shipbuilding infrastructure dominated by steel for large structures, attaching composites is a difficult but achievable task. Deck to hull joints, including FRP house to metal hulls and metal to FRP hulls are the largest and most important types of joints. These joints usually are made by a combination of bolting (in slotted holes to allow some differential expansion and contraction) and bonding (with an elastomer that retains its seal but allows some movement). The retrofit attachment of a composite director room onto the steel deckhouse of anAegis class destroyer (4), shown in Figures 21.2 and 21.3, is a highly loaded rigid attachment requiring thorough engineering and testing. There is ongoing research into the use of adhesive bonding of composite structure to steel structure and if successful this would eliminate the need for bolting.

For lesser attachments, self-tapping wood screws can be used. Adhesives such as methyl-methacrylates and high strength epoxies will make adhesive joints as strong as the composite base laminate. Again, managing the local concentrated load of the attached item(s) must be considered.

21.4.7 Details

The key to making composite structures work is in the details. It is common knowledge that composites do not corrode, have high strength for low weight, have low panel stiffness that can be solved with sandwich structures, etc.

Despite these advantages, composite construction has some features that require special details. Following is a partial list of details from a sandwich core manufacturer's design guide (11):

- bulkhead detail with putty fillets,
- bulkhead detail on foam pad,
- solid centerline detail,
- cored centerline detail,
- stringer with putty fillets-separate tabbing,
- stringer on foam pad-separate stringer tabbing,
- stringer with putty fillets, inside skin tabbing,
- stringer on foam pad, inside skin tabbing,
- stepped chine, high density insert,
- stepped chine, foam wedge,
- stepped chine detail-putty radius,
- stepped chine detail-putty radius,
- hard chine with laminate overlaps,
- hard chine with high density insert,
- hull to deck joint detail #1,
- hull to deck joint detail #2,
- through hull fittings,
- winch pads,
- mast step and keel bolts, and
- chain plates.

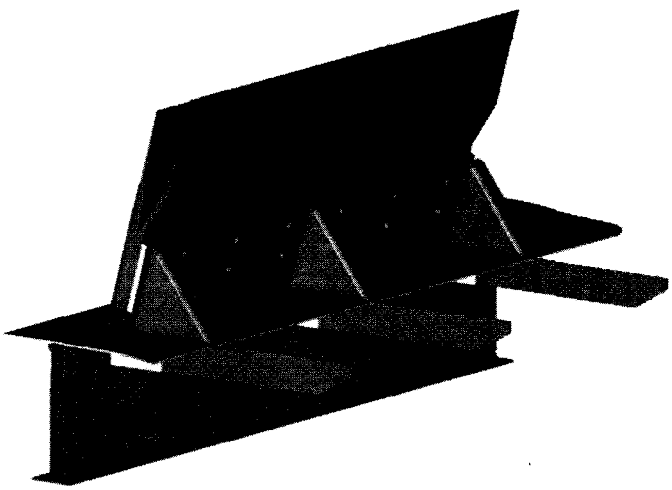

Figure 21.2 Director Room Attachment

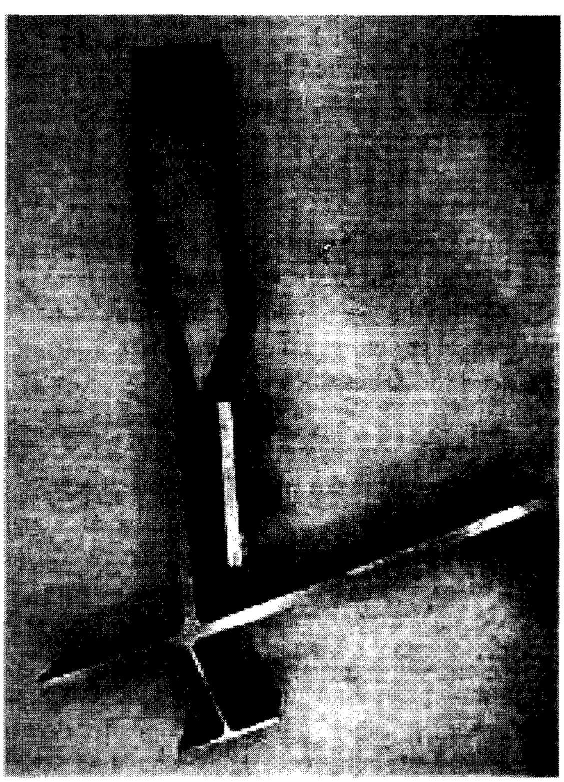

Figure 21.3 Director Room Attachment Detail

Many of these details are extensions of details required by classification society guides and rules expanded to capture the experience of various builders and manufacturing processes. A sampling of these details is shown in Figures 21.4,21.5,21.6 and 21.7.

Figure 21.4 shows a typical method of laminating a stringer to the hull (or other panel) shell. A foam pad is used at the base to avoid hard laminating acute angles. The tabbing laminates are wrapped from each side of the stringer, over the top and stopped. This sequence makes laminating easier and doubles the thickness of the layers at the top, where the strength is needed.

Figure 21.5 shows a chine/spray rail detail. The bottom outside skin is carried though the chine and up the side a bit, the side skin is carried down through the chine and onto the bottom a bit. Then the bottom and side core is installed with an extra wedge im~ideto stiffen the chine, and then the inside skins are similarly carried through the chine.

Figure 21.6 shows two methods of attaching through-hull fittings to a sandwich structure. On the left, the position ofthe fitting is preplanned and a section of high-density core material inserted in place of the fitting. Then the hole for the fitting is drilled and the fitting inserted with appropriate bedding compound. On the right, the fitting is inserted into an existing low density cored sandwich laminate by drilling the location, routing out the core, filling the hole with a high density putty, then re-drilling the hole and installing the fitting.

Figure 21.7 shows how a winch can be attached to a sandwich deck. High-density core is installed and the skin laminates locally doubled to distribute the loads from the winch. These local reinforcements are faired out into the rest of a panel or to major stiffening members. With a large backing plate, the winch can be bolted on. If the backup to

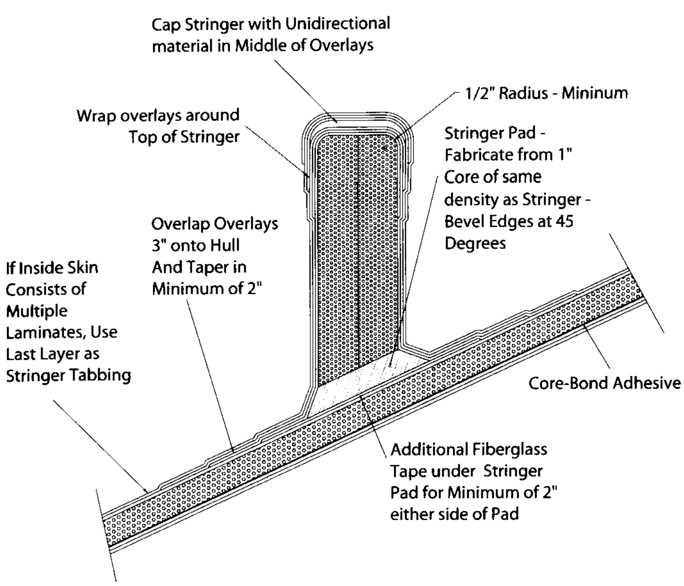

Figure 21.4 Composite Girder/Longitudinal Detail

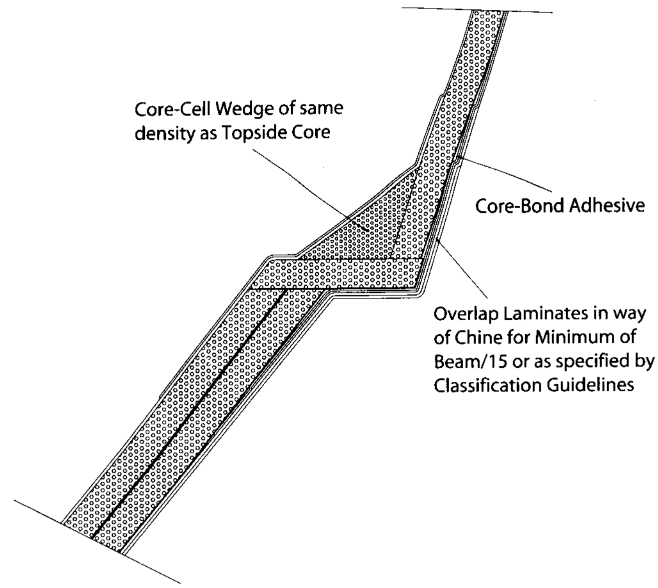

Figure 21.5 Composite Chine/Spray Rail Detail

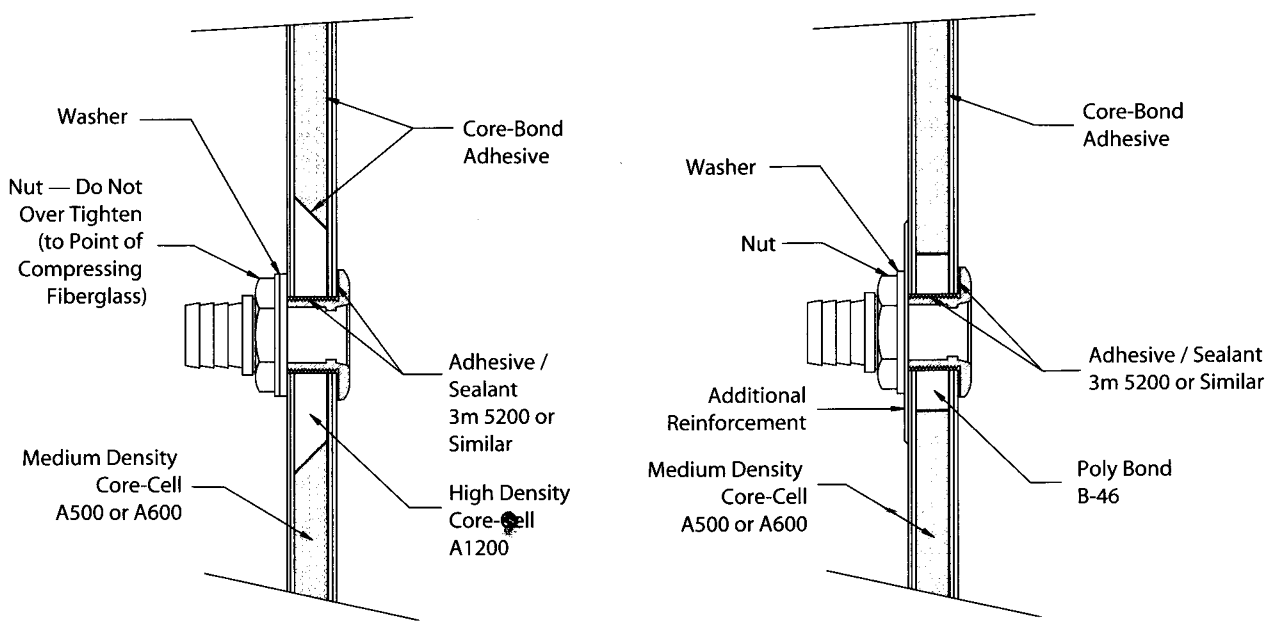

Figure 21.6 Through-hull Fitting Attachment

the bolts is only washers, a tubular insert is recommended to take up the compression loads from the bolts.

21.5 MANUFACTURING METHODS

21.5.1 Forming the Shape

There are many different ways to form composites. A complete structure may use a number of these methods. Only the basics are covered here. Full coverage of all systems is beyond the scope of this chapter but can be found in many of the references.

21.5.1.1 Molds: female and male

Female molds are the most common method of establishing the shape for composite parts. They are usually made by applying fiberglass with special tooling resins over another part or a temporary male shape. Female molds also can be made directly from combinations of wood frames and sheets covered by fairing and mold compounds.

To allow easier worker access, some female molds for

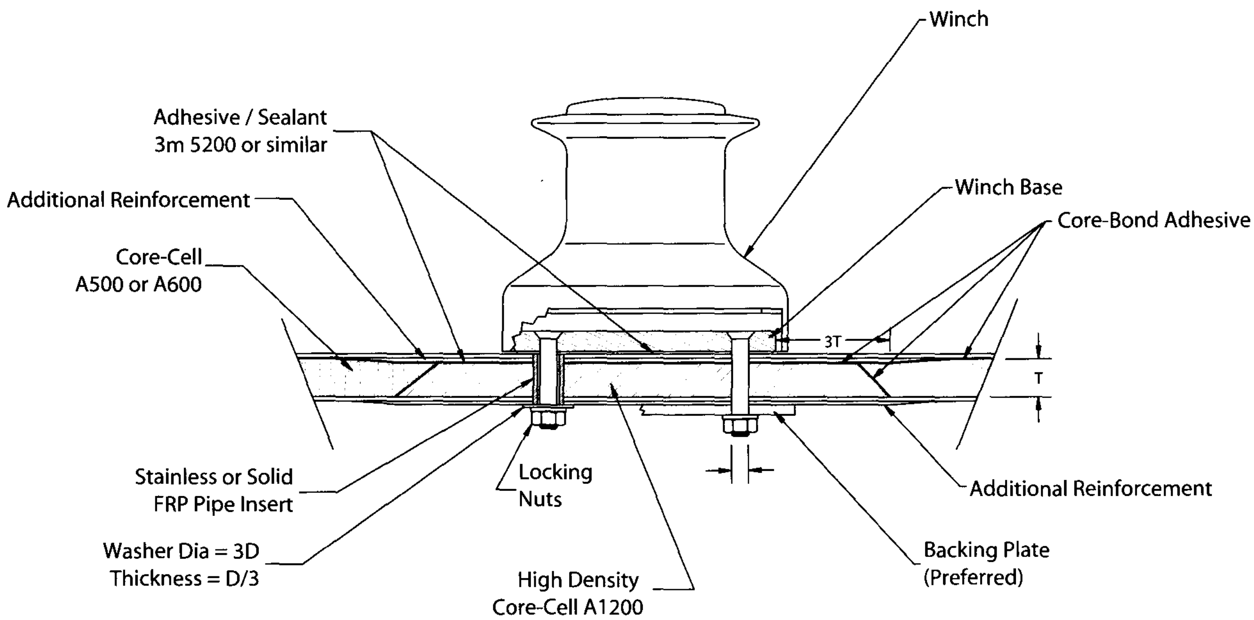

Figure 21.7 Concentrated Load Detail

boat hulls are made with a split seam down the centerline. Each half-side of the hull can be laminated more easily down hand, leaving some of the laminate layers out of the keel and stem area. Then the molds are bolted back together and the rest of the laminates are used to join the hull half-sides together.

Matched female molds are used for resin transfer and resin injection molding. These are heavily formed tools to take the pressure of the laminating methods. The extra tooling can be justified by multiple runs of smaller parts, roughly 1 m^2.

Male molds are, simply enough, just the opposite of female molds. As it is the outside surface that is usu<1l1y the exposed *show* surface, the mold does not need to be Rnished nearly as nice, so it is easier to make the male mold. However, the outside surface must then be faired and painted. Male molds seem to be popular for mid size sailboat construction as many of these are custom projects, and working over a 10-20 m hull is easier than making a female mold for one project and working inside.

21.5.1.2 One-off and custom methods

A number of methods are available for making one-off and custom composite parts. Generally, if three or less parts are to be made, it is more cost-effective to use a one-off method.

An early one-off method was described by Johannsen (7) (also illustrated in Chapter 5 of reference 2). Sections at regular stations are cut out (usually wood) and placed on a sturdy frame. Battens are nailed over the stations to form a male shape. Then structural foam sheets or planks can be formed temporarily over and nailed to the battens. When the planks are all fitted, with the butts and seams bonded, they are attached to the battens from the inside with wood screws. The temporary outside nails or screws are removed and the holes plugged. The outside of the foam can be faired as necessary and is now a foam *plug.* The required fiberglass skins are laminated to the outside and faired. Then the whole assembly of wood, foam and fiberglass is turned over and placed into and secured to a sturdy cradle. The wood forms and wood screws are removed, and the inside skin is laminated.

With the one-off method, the hull shell (or other part) is formed without going through the time and expense of making a male plug and female mold that may be used only once or twice.

A natural extension of this method is the bead and cove method perfected by Bilodeau (12) and shown in Figures 21.8 and 21.9. With a new kind of SAN (Styrene Acrylo-Nitrile) linear structural foam, Bilodeau discovered that the foam could be machined easily and reliably into different width bead and cove planks (Figure 21.8). The sections are made into the male frame based on the thickness and density of foam used. No battens are necessary. Each bead and cove plank is bonded to the previous plank line with specially made putty that is strong enough to bond the foam but soft enough to fair the foam shape.

As each line of planks is bonded together, the foam shell becomes quite stiff, eliminating the need for battens.

Some temporary fasteners are used, but many fewer than with the previously described method. Wider planks are used in areas of less curvature. Plain flat sheets are used in flat or mostly flat areas. The foam is faired and the laminates applied as before. One-off construction requires extra fairing and painting, but is still efficient for custom work.

21.5.1.3 Build-up from panels

Large parts also can be made by joining a number of flat or nearly flat panels. Westport Shipyard in Westport, Washington used to make 3 m x 9 m gelcoated FRP panels on a large flat glass table. They could pick this panel off the table and place it into a basic female slat frame. Some laminates were left out of the butts, which were joined later with additionallayers, similar to joining hull halves. Then they had a finished outer skin in a female frame to which they could apply core material, the inner skin, and the rest of the structure. They had variable beam bow molds, hinged at the stem, to allow the building of a number of different sized hulls from the same tools.

ATL Composites in Queensland, Australia have developed the Duflex® system to build [mainly boat] structures out of joined, prelaminated, flat sandwich panels. Standard panels are 1.2 m x 2.2 m with a *Z-Joint* machined into the edges. This joint has a 15/1 scarf in the top laminate, a square butt for the core, and another scarf for the bottom laminate. They can be NC cut at the factory into numbered pieces that are joined at the job site using epoxy adhesives.

There are many variations of the methods mentioned. Easily formable composite materials are an enabling technology.

21.5.1.4 Modular construction

The same kind of advanced and reliable adhesive technology that allows one-off methods such as Duflex also allows modular construction in composites. The VISBY corvette (13) is being built with flat sandwich panels with some material held back at the butts and seams. Then additional material is placed into the joints and they were infused with vinyl ester resins. A similar method is used to join major hull sections.

Some key optimization decisions need to be made to determine if the structure is to be built as large parts or modular units later joined together. Continuous laminating FRP allows large parts with an uninterrupted smooth surface. Steel parts must be built up from limited plate sizes that can be butt-welded efficiently and quickly. Composite parts usually require additional reinforcements at large joints.

A compromise solution is for large hull parts to be manufactured in a continuous fashion with smaller parts such as bulkheads, deck sections and superstructure sections planned into separate assemblies or blocks. Modular construction is a relatively recent feature for most large yacht builders, although Vosper Thromycroft, in the UK, used it extensively in the construction of the Royal Navy's mine hunters.

One type of modular construction used by many pleasure boat builders and fabricated (multiple) parts suppliers is to use molded grid sections for the framing system. A separate mold is made to include the longitudinal and transverse framing system for a boat. It is generally easier to

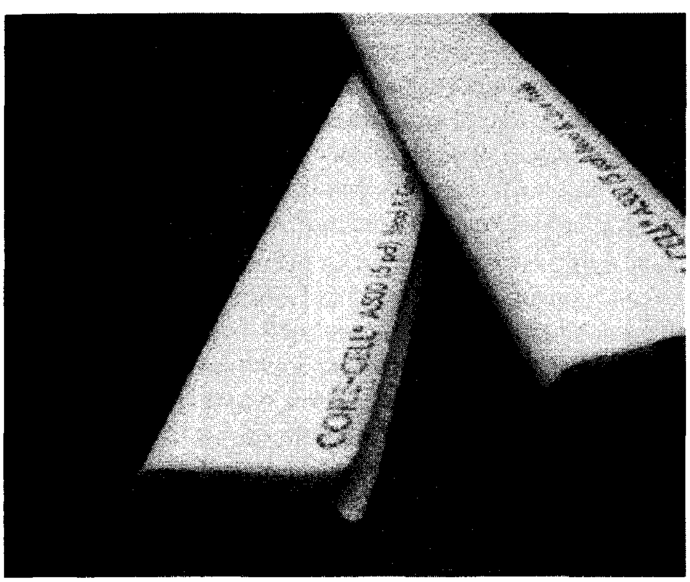

Figure 21.8 Bead and Cove Planks

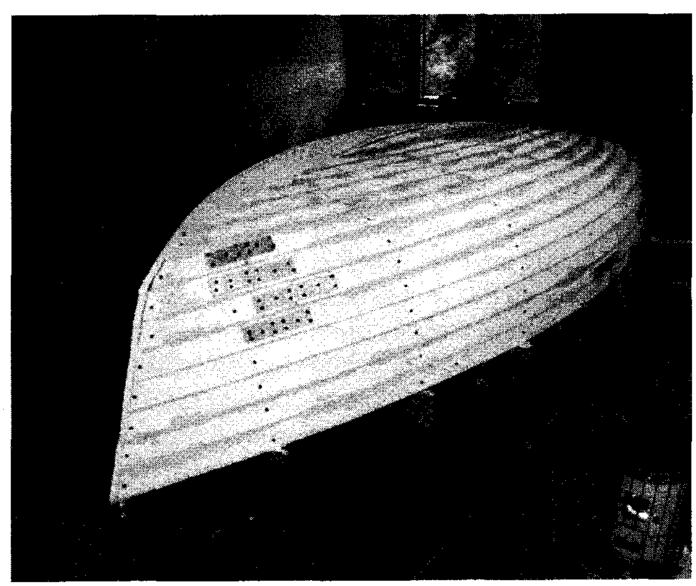

Figure 21.9 Bead and Cove Construction

laminate on this mold than down inside a female mold. Then the liner or grid is removed from the mold and bonded to the shell to form the stiffened part. Some of these grid molds are male molds that also contain a partial liner for the hull. When installed, there is a smooth ge1coated surface on the inside.

Most of the advantages of steel or aluminum block construction, such as inside shop construction, zone outfitting, and zone painting can be realized with composites. The main consideration for composite blocks is that they are likely to be less stiff than similar sized metal blocks, so heavy outfitting attachments and rigging for movement must be specially considered.

Accuracy control can be a problem as the various thermoset resins used for most polymer composites will shrink some after lamination. However, the edges are easy to trim and the butt and seam joining adhesives and laminations can fill moderate gaps of a well-designed scarf joint.

21.5.2 Material Application

One of the nice advantages of composites is that they can be formed easily into complex shapes. The materials are applied with a liquid resin that, with the right fabric for the job, can be sprayed easily or applied to a mold surface. Special spray fillers and putties can fill or build up more difficult places. A brief look at the different material application methods follows. Scott (1) and Greene (2) have more indepth descriptions with multiple photographs and diagrams.

21.5.2.1 Resin mixing

Polyester and vinyl ester resin mixing can be done a number of ways. The simplest and most common is to measure the proper volume of resin into a bucket, then measure the right amount of catalyst out and stir it into the buc1~t. On a nice 21 °C day, the laminator may get 1/2 to 3/4 hour working time before the resin starts to gel. That is IF the proper amounts were measured, the resin is really at room temperature, the catalyst chart was read properly, and the catalyst is fresh, all among other variables. This is often where the laminating process, which seems simple from the outside, becomes a bit complicated.

Catalyst ratios for poly and vinyl ester resins are usually on the order of 1.5% to 2.5% of Methyl Ethyl Ketone Peroxide (MEKP), sometimes Benzoyl PerOxide (BPO), adjusted for the shop temperature and laminating method. Too much catalyst, and the resin can kick too quickly, lose some of its physical properties and cause too much exothermo Too little and the resin will not cure right. The resins can react differently with different makes of catalyst. Mixing by weighing the liquids instead of judging volumes is better, but it is still necessary to keep track of the many variabIes. Thus the use of internal mix laminating equipment is becoming more popular.

Epoxy resins are easier to mix, as they are more nearly equal parts of resin and hardener. Epoxies give off fewer Hazardous Air Pollutants (HAPs), but exposure can sensitize workers to the point they can no longer be around the resin.

21.5.2.2 Sprayup

The most basic of the lamination methods is to spray the resin from a mixing gun into (or onto) the mold. Some guns chop and blow short glass fibers into the stream, *chopper spray gun* (see next Subsection). Some are just used to get resin onto the part to wet out the dry fabrics. Older guns mix the catalyst in the air outside the nozzle. Newer technology mixes the catalyst in the gun near the nozzle to give better mixing. This provides for quick easy coverage of the mold or part. However, all the tiny droplets also present a lot of surface area to the atmosphere and produces higher HAPs. Volatile Organic Compounds (VOCs) was the previous defining negative term for the airborne byproducts of laminating with organic resins. Either way, reduction of airborne pollutants is quickly changing the lamination methods of the composites industry.

21.5.2.3 Chopper Spray gun

A chopper gun is a special spray gun that has rotating knives that chop continuous glass strand rovings into short glass fibers. It is easy to form these wetted fibers into various shapes. Typical of products produced solely from chopper guns are fiberglass bathroom fixtures and hot tubs. Because there are no binders with chopped glass as there is with fiberglass mat, there are advantages of having a chopped skin coat on a boat for blister protection. A chopped laminate generally has a low glass content (see Table 21.IV) and low strength, but is quite economical, apart from controlling the HAPs.

21.5.2.4 Hand layup

Hand layup is characterized by manually wetting dry fabrics and consolidating this wetted fabric into the mold. Fabrics can be back wetted, where resin is first applied to the part, then the dry fabric laid in, then a serrated roller used to force the fabric down into the resin so that the resin flows up through the fabric and forces the air out. Resin drainage before fabric application must be watched to make sure there is enough resin to properly wet the upper portion of a vertical surface is another variable that must be taken into account. The resin can be formulated with a thixotrope to keep it from draining too fast,. Glass content can be anywhere from 30% to 50% depending on the type of fabrics used and the skill of the laminators.

With the messiness involved in hand laminating methods, workers are usually clothed in throw-away protective suits (Tyvek coveralls are popular) including booties. Most wear some kind of respirator.

21.5.2.5 Impregnators

Resin impregnators are sets of rollers that hold a pool of catalyzed resin. As the dry fabric passes through the resin pool, it gets wetted and is passed down through the machine ready to be placed into or on the mold/part. From a manufacturing point of view, the best approach with these machines is to mount them on overhead cranes with rotating turrets so wetted fabric can be placed at any angle in a mold. Fabrics can be cut to strips and dropped down on top of stringers also. HAPs are reduced, as there is no spraying and less exposed resin. Glass content is higher than hand layup and can range from 45% to 65% glass by weight, depending on the type of machine, the type of fabric, and how the machine is set. Worker exposure is reduced, but protective measures are still usually needed.

21.5.2.6 Resin infusion

With infusion, dry fabrics and/or cores are situated in the mold then enclosed in a vacuum bag. The vacuum pulls catalyzed resin into the fabrics and core, from many ports for large parts, until the whole part is totally wetted out. This method gives a high glass content (60 to 70%), a generally void free laminate and a reliable bond to the core in a sandwich laminate. However, infusion is not for the unskilled and the weight savings in the skins is partially offset by the weight gain in the core.

The most common of the infusion methods is the Seemann Composites Resin Infusion Molding Process (SCRIMP). this is a patented process that uses a number of vacuum and resin ports along with a distribution medium to pull resin into the part. There are a number of variations on this theme, but the basic principle is the same. Infusion reduces HAPs and makes for a worker-friendly environment.

21.5.2.7 Prepregs

With pre-impregnated fabrics, the catalyzed resin is already in or on the fabric. Some forms of prepregs must be refrigerated until they are placed in the mold, but then they cure very slowly at room temperature resulting in a lot of working time. They are usually supplied with epoxy resins and carbon fiber reinforcements, and used in more advanced projects such as aircraft and racing yachts.

The basic approach with prepregs is to apply the fabrics to the part in multiple layers to suit the design. Then a release film, bleeder cloth and vacuum bag (or sealing bag for an autoclave) is placed over the part, vacuum is pulled (or pressure is applied) and heat is applied. Cure tempe~atures can range from 80 to 135°C for anywhere from 1 'to 10 hours, depending on time, temperature and pressure.

Prepregs yield high reliable glass contents. They are the most expensive form of material, but there is little waste. Additional adhesive films must be used to provide the extra resin to bond to core materials. As a closed molding system with very little extra solvent for the resin, there are no HAPs.

21.5.3 Quality Control

Quality Control in composite construction is more challenging than for steel or aluminum mainly because non-destructive test (NDT) methods for metals are fully developed and cost effective. The outward appearance of a weld is a fairly good indication of its quality. The outward appearance of a multi-layered composite E-glass laminate reveals that the surface layer has a reasonable glass content and that there are an acceptable number of air inclusions in the surface and first subsurface laminates. Past that, there are no economical NDT means of determining the quality and strength of the laminate. Hammer testing is a crude way of testing for voids and lack of bonds. Moisture meters can check for water content of the laminate. Thermography can see through a laminate to the core but not past it. X-rays and certain ultrasound techniques can show some additional defects. Special fibers can be bonded into a laminate to show a degradation in strength beyond a norm.

However, the better methods are not cost effective for the majority of builders. Basically, the marine industry cannot afford the level of QC common in the aerospace industry. The best QC is to ensure quality in the building process. The latest guide from the American Bureau of Shipping (14) has an extensive section on QC measures needed to achieve quality construction.

21.6 REPAIR

Repair of composite structures is not that much different than of other structures. It is just that the repair materials and the bond may not be as good as original (a primary bond), so special consideration must be given to the nature of the damage, the repair procedure, and the intended loading for the damaged area.

21.6.1 General Repair Guidelines

A primary bond is that bond achieved in a window of usually 1 to 3 days after the preceding laminate was completed. In the primary bond window, the chemicals in the resins still achieve a good amount of chemical cross-linking. A primary bond is usually maintained in the continuity of new construction. With a secondary bond, the window has passed and the next laminate is only adhesively bonded to the existing laminate. Some resins are better at secondary bonds than others. Vinyl esters are usually better than polyesters. Epoxies are usually better than vinyl esters. Epoxies can have a problem if the base laminate is a poly or vinyl ester laminate and is not fully cured.

The biggest concern in composite structure repairs is that the vessel or structure has been in operation for a number of years, the laminates are old, and the bond to the old laminates definitely will be a secondary bond and not nearly as good as factory original construction. Proper laminate preparation and use of better materials can make a properly designed repair just as good as the original structure, often even better.

Composites also can be used to repair steel vessels. Around 1990, the San Diego Maritime Museum was faced with losing the Coast Guard certificate for its old steam yacht MEDEA due to deteriorated steel hull plating. She was saved and permanently repaired using a foam core bonded to the outside of the steel with a vinyl ester resin, and a new FRP skin over the foam (15,16).

One thing to avoid in repair is the temptation to make the repaired structure better than the original. The repaired area would then be so much stiffer and stronger than the existing structure, that a hard spot can be accidentally inserted into the structure, possibly causing more problems.

21.6.2 Repair Joint

Coast Guard NVIC 8-87 (16) shows a typical repair joint, reproduced in Figure 21.9. The damaged area is cleaned out, the damaged core material is routed out, the edges are tapered into a scarfed joint, a temporary backing plate is used as a mold, the outside skin is laminated, new core is bonded in, and the inside skin is laminated. This is an old picture, but shows that many of the basics have been around for a long time. This repair assumes access from the inside of the vessel.

Blind repairs can be made from the outside using a lost mold inside. Depending on the loading on the damaged area, some additional reinforcement may be necessary to assure adequacy. If the original plans are not available, a burnout test on a sample of the damaged laminate should be done to determine the original laminate schedule. If the damage is related to structural inadequacy, the repair should be in excess of the original and the rest of the structure reassessed.

21.7 SUMMARY

The use of composites in the marine industry has a long and varied history. Few doubt the advantages of composites for small craft. The hanging question is how large can a FRP vessel be and still be a small craft. The 57 m U.S. Navy MHCs are surely not small craft. Sweden has extended the composite size range up to 73 m with the VISBY Corvette.

Over 30 years ago a GRP freighter was researched (18). There were a number of problems identified; the main ones were fire protection and global stiffness. Fire, smoke and toxicity protection concerns have been addressed in modem passenger and military vessels (19) where the need for high speed encourages the use oflight-weight composites, albeit with additional safety measures. Global stiffness can be addressed by a number of means, including rearranging the structural shape to be stiffer (20) or through extensive use of carbon fiber (13).

Composite vessels can be lighter and better performing than aluminum (21). There are obviously certain advantages and disadvantages to every material. The evolution of composite materials, design, and products continues.

This chapter is only an introduction to FRP design and construction. The interested reader is encouraged to investigate additional information in the references and related materials.

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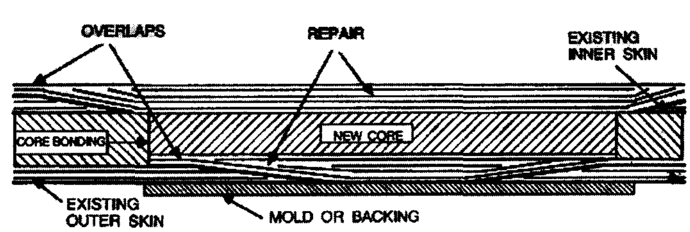

Figure 21.9 Repair Joint from USCG NVIC 8-87

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CHAPTER 22

General Arrangement Design, Hull Outfit and Fittings

Hans Hofmann and Thomas Lamb

22.1 INTRODUCTION

This chapter contains a general discussion on general arrangement design, and descriptions and illustrations of hull outfit equipment and fittings in sections 22.2 through 22.10.

It has drawn extensively from the previous edition of this book (1), Chapters IX and XII, as much of the information has not changed. However, the information has been updated where necessary and new illustrations have been used when appropriate.

Section 22.2 describes the basic development of general arrangements. All of the specific ship type chapters in Volume II show typical general arrangements for each of the types covered in the chapters. Only the basic aspects that are applicable to all of them are covered in this chapte'6

Section 22.3 describes accommodation arrangementfle-sIgn.

Section 22.4 describes closures such as watertight doors, including large vehicle access doors, and similar joiner and weathertight doors. Cargo hatch covers, access hatches, manholes, and other small closures are also discussed. A description of other openings such as freeing ports and cargo hold ventilation openings is provided.

Section 22.5 discusses anchoring and mooring arrangements and deck fittings including mooring fittings, bulwark, safety rails, and vertical and inclined ladders. This section also describes stores handling equipment, deck storage fittings and lashings, as well as the stowage of spare parts.

Section 22.6 describes pilot boarding equipment and its arrangement and design, and includes a discussion of regulatory requirements.

Section 22.7 discusses the design arrangement and installation of battens, dunnage and cribbing in cargo spaces.

Section 22.8 discusses deck coverings including the large variety of current materials used and a typical material selection and installation.

Section 22.9 describes the design and installation of joinerwork, insulation and lining systems. It includes discussions of the regulatory body requirements and other design rules and practices. However, insulation for fire integrity is covered in Chapter 16 - Safety.

Section 22.10 discusses the requirements for furniture, furnishings and steward spaces. It describes the design and use of furniture, including upholstery, drapery, carpets and linens, as well as descriptions oftypical commissary equipment.

22.2 GENERALARRANGEMENT DESIGN

The design of a ship's general arrangement can be a very rewarding one, especially if the designer gets the opportunity to see the product as it is being constructed as well as when it is finished.

The arrangement of a ship is dictated by the service it provides. For example there are basic arrangements for tankers, bulk carriers, container ships, car carriers, cruise ships, offshore supply vessels, ocean-going tugs, harbor tugs and fishing vessels (see the specific ship type chapters in Volume 11). They have all developed over time to provide the best compromise for the safe and efficient operation of the ship. While it is unlikely that a ship design will be a failure as long as the basic arrangement is followed, arrangement design can make the ship more of a success and a pleasure to operate. A superior design needs to be a well-analyzed and excellent compromise between the various individual systems and configuration requirements for the specific ship.

There are a limited number of books available that cover general arrangement design, but not in the English language. Previous editions of the present book have covered the subject, but only in a brief overview. There have been a few technical papers given to professional societies (2-9) on the subject and also in ASNE for space analysis and relationships for naval ships (10-13). The U.S. Navy has also developed guides for the preparation of General Arrangements (14-16).

The design of the general arrangement of a ship is one of the most important design aspects and one that must be decided early in the design process. Even in the Concept Design stage it is likely that a *Sketch General Arrangement* will be prepared. This is because all other design aspects depend on and must be integrated by the general arrangement. Structure must be arranged to suit the general arrangement layout of holds, tanks, machinery space, and deckhouse. The cargo handling gear must be located for efficient loading and unloading of the cargo and be integrated into the structural arrangement to ensure adequate support, and so that the loads can be distributed into the hull structure.

However, the general arrangement designer has to understand the structural designer's need for structural member continuity, and the smooth distribution of load throughout the structure, and thus select the correct location for the major boundaries of the spaces (see Chapter 17 - Structural Arrangement and Component Design). The major compartments have to be arranged to provide acceptable trim on the various operating conditions the ship will experience in service. The smooth flow of the cref as they perform their work functions, and those necessafy in any emergency is essential. Finally, recognizing that the crew will spend most of its life onboard the ship, a high standard of crew comfort must be provided.

Thus the general arrangement designer must work closely with the other designers to ensure that the design is fully integrated.

There are national laws and international agreements that must be met in the design of general arrangements for merchant ships. These requirements are:

International

- SOLAS, International Convention for Safety of Life at Sea 1974, including the Protocol and all Amendments.
- IMO, International Maritime Organization
- Panama Canal Company Rules
- Suez Canal Rules

National (U.S.)

The USCG enforces compliance with the following nationallaws:

- Code of Federal Regulations (CPR). CFRs are on the Internet and also available as hard copies from the U.S. Printing Office. Typical CFRs dealing with general arrangement design are:
  - 46 CFR Transportation
  - 49 CFR Hazardous Material
  - 35 CFR Panama Canal
- NVIC Navigation and Inspection Circulars. These are issued by the USCG as an advanced notice for pending new regulations and are preliminary guidance documents, which are usually canceled when the new requirements are formally incorporated into the appropriate CPR.
- U.S. Public Health Service (USPHS) Pub. 393, Handbook on Sanitation of Vessel Construction. This booklet delineates the requirements for Food Services, Potable Water Generation and Stowage, Marine Sanitation Devices, HVAC and Deratization.
- International Labor Organization (ILO) Regulations on Crew Accommodation, and
- Regulations issued by Country of Registry Maritime Administrations.
- Labor Union Agreements, Crew Numbers and in some cases details of Accommodation Amenities are sometimes governed by these agreements. These requirements vary between shipowners and usually provide higher standards than CFR 46.

It should be noted that the country of registry regulations can be stricter than the SOLAS and ILO regulations.

So how does a ship designer learn the art of ship arrangement design? The usual way is through working with others experienced in the art and learning from them. The nuances in developing accommodation arrangements can be written down, but the need for, and best solutions regarding different crew and officers not using each others passageways in their daily activities is something that can only be learned by practice. Today, ship's crews are multi-national and multi-sex, and this can increase the challenges found in the development of effective accommodation arrangements. Recent merchant ship designs provide single staterooms for all crew members with either individual toilet and shower (T&S), or as a minimum individual lavatories with a T&S shared by two adjacent staterooms. These arrangements provide inherent gender segregation and, therefore, ease the accommodation of mixed gender crews.

A good way to gain experience in ship arrangements design is to review and analyze the ship drawings presented in the marine magazines and Technical Journals. Typical arrangements for commercial designs can be seen in the RlNA *Significant Ships* publication. Things that should be looked for are:

- any innovate departures from the normal ship type arrangement?
- how are areas related to each other?
- is there anything that does not appear to make sense?
- what would you have done differently and why?
- how are the different crew members located in the deckhouse?
- how good is the access/flow for crew members to their work, lifeboat muster stations, food service lines and leisure spaces?
- is the machinery casing internal or external of the deckhouse?
- is noise generating equipment adequately segregated from crew work and living spaces?
- what cargo handling gear is used for the commodity to be carried?

In addition:

- develop a collection of ship arrangements that are particularly liked/admired, and note on them the date of the design and what is special,
- review ship's furniture manufacturer's catalogs to develop an understanding of item sizes,
- become familiar with standard accommodation lining and ceiling systems,
- become familiar with standard cabin module concept and a manufacturer's line of modules,
- become familiar with cargo handling gear and systems, and
- become familiar with regulations influencing arrafgement design.

The ship arrangement designer has to deal with the shipowner's preferences and merge them with the prospective shipbuilder(s) build strategy and production methodologies. The best way to develop the necessary good understanding of the shipowner's preferences is to establish a close liaison with the shipowner's technical representatives and obtain arrangement drawings of the shipowner's most recently acquired ships; but again it is important to note the date of the design. This is important because of the numerous changes of pollution and safety requirements that have occurred in the recent past and are still occurring at a rapid pace. Little things like inclined ladders fore and aft or athwartships can be gleaned from the drawings. If drawings are not available, visits should be made to the shipowner's ships and both photographs and video taken for later review.

The development of general arrangements for a ship has to result in the best possible combination of all required systems into a single efficient *system of systems* that p~ovides an efficient ocean transport. The designer should always remember that the reason the shipowner invests in a ship is to make a profit when providing the offered services. Thus while crew access and amenities are important, the arrangement for the cargo or service that the ship will carry or provide must be the driving focus. That this is so can be seen from recent ship arrangements that have located the deckhouse as far aft as possible on commercial ships. Every naval architect knows that the best place to be on a ship in a seaway, relative to motions and propeller noise and vibration, is amidships at waterline level. Yet today many ships are designed, as previously mentioned, with the deckhouse as far aft as possible. This provides the best solution from the cargo point of view and also brought about the use on ships of the free-fall single lifeboat instead of two lifeboats in davits, which cannot be located aft of a certain distance forward of the propeller(s) as delineated in the 46 CFR. The extreme aft location of the deckhouse may not be the best from the point of view of crew comfort but is usually the best for the cargo arrangement. Therefore, it can be seen that the best arrangement will be a compromise between many conflicting requirements, which the ship general arrangement designer must address.

When developing the deckhouse configuration the designer must check that the conceptual structural configuration provides the required continuity of the bulkheads, girders and stanchions from the hull into the deckhouse. The designer must also determine whether the HVAC designer intends to use a conventional or a *Higher Velocity* HVAC system. The higher velocity system uses smaller cross section ducts, which allow the arrangeJllent designer to use lower individual deck heights while still maintaining the required interior headroom. In addition to the weight savings this also lowers the combined deckhouse center of gravity, which of course helps the stability. The deckhouse designer must develop fire zones and should discuss with the structural designer the location of steel bulkheads in the deckhouse and their possible use as fire zones. The machinery arrangement concept must be reviewed to assure that the engine air intake and exhaust, as well as the engine room ventilation system, are well integrated into the deckhouse. This is important even if at the present time the stack is a separate structure aft of the deckhouse to provide best noise attenuation.

The designer of the deckhouse must consider the required locations of the Navigation Lights to assure there are proper mounting points available on the house and mast. These mounting points must have good access for maintenance.

At this point it is prudent to determine the *eye height* required for the helmsman to obtain proper visibility from the bridge. For a stand-up helmsman the eye height above the bridge deck is 1.6 m. From this eye height the helmsman must be able to see the water surface at a point 1.5 ship lengths forward of the forward perpendicular (FP). This is considered the minimum.

The arrangement of the wheelhouse is usually a combined effort of the shipowner, shipbuilder and the classification society. Today all classification societies will give guidance for and special class notation if the wheelhouse is designed to suit their rules. Figure 22.1 (a) shows a diagram from Det Norske Veritas Rules for wheelhouse equipment layout and Figure 22.1 (b) shows photographs of the bridge for a recently delivered ship and (c) shows a proposed *one-man bridge* arrangement.

The arrangement of the crew on the various decks can follow a number of concepts as shown in Table 22.1. The captain's accommodation should always have a side view to starboard.

If the ship design is for a foreign shipowner certain cultural aspects of the intended crew will need to be known. **It** is obviously wrong to assume that what is acceptable for U.S. shipowners will be the same for foreign owners. For example, bars are prohibited in officers and crew lounges on U.S. and Islamic owned ships but are common on aU,others, including British and European warships. If the Chief

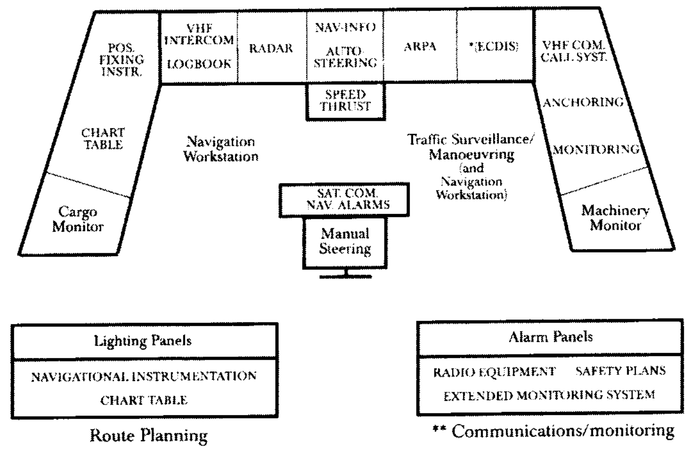


Figure 22.1 (a) Modern Bridge Design—Arrangement of Wheelhouse Equipment Based on Det Norske Veritas

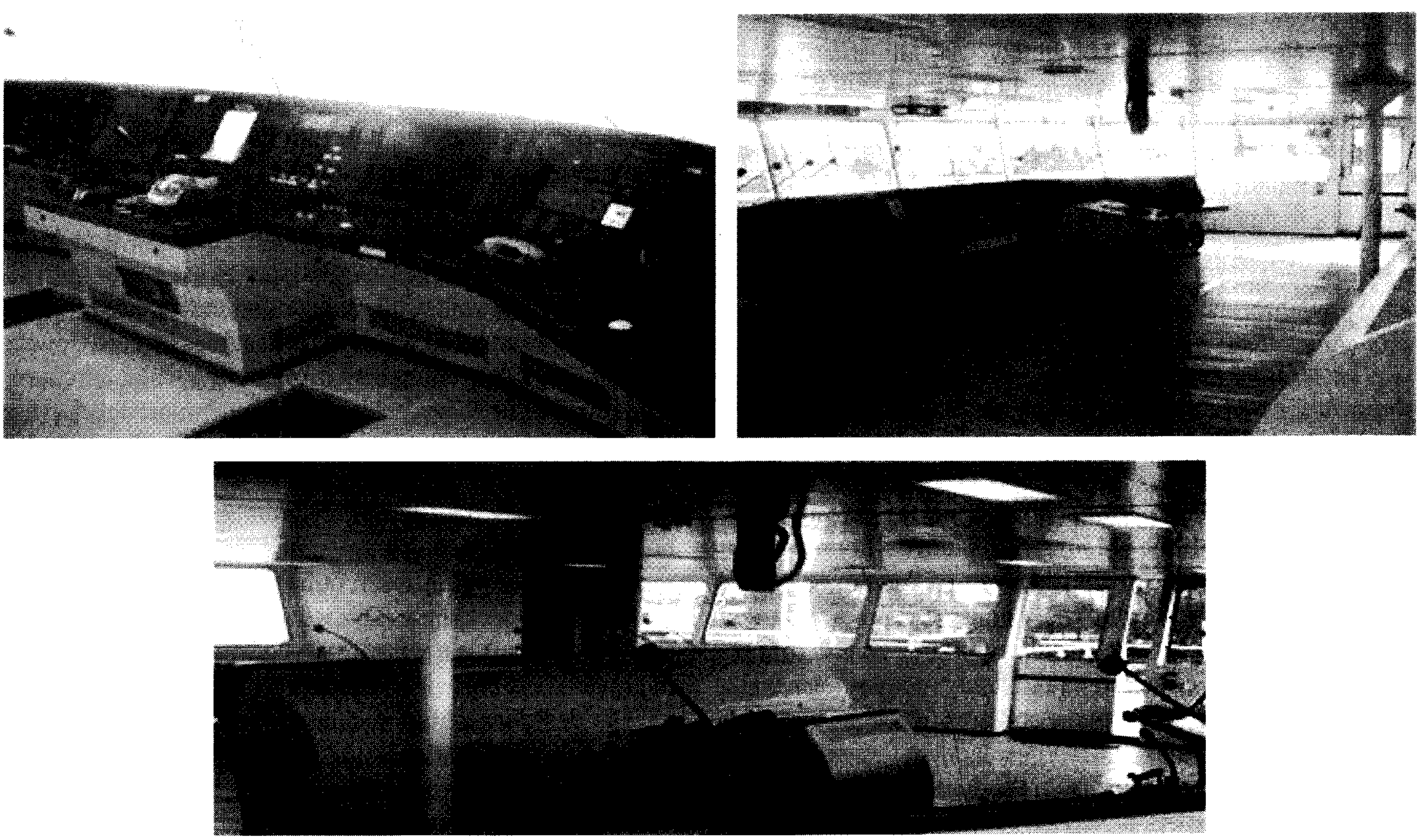
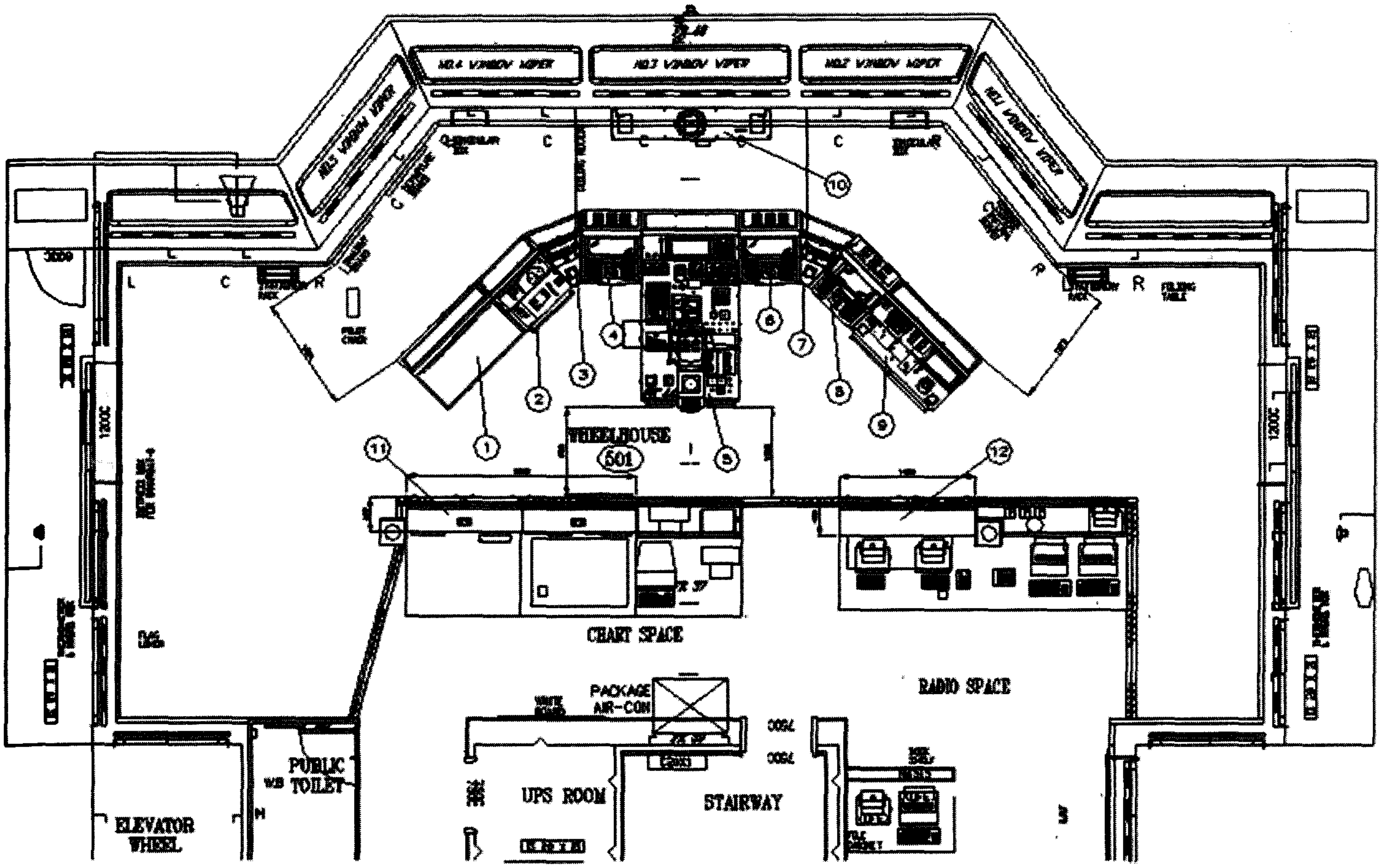
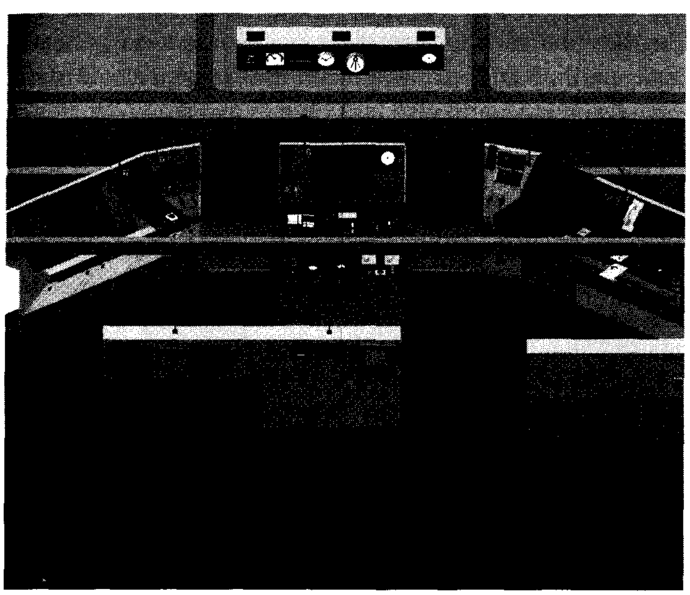


Figure 22.1 (b) Modern Bridge Design—Typical Bridge





NO	DESCRIPTION
1	1250mm ROUTE & CHART CONSOLE
2	740mm NAVIGATION CONSOLE
3	45 DEGREE NAVIGATION CONSOLE (PORT)
4	NUCLEUS 3 6000A ARPA RADAR
5	1100mm CENTRE CONSOLE
6	NUCLEUS 3 6000A ARPA RADAR
7	45 DEGREE SURVEILLANCE & MONIT. CONSOLE (STBD)
8	NUCLEUS 3 6000E ECDIS
9	1300mm SURVEILLANCE & MONITORING CONSOLE
10	1800mm OVERHEAD CONSOLE
11	2590mm GROUP PANEL CONSOLE (PORT)
12	1525mm GROUP PANEL CONSOLE (STBD)

Figure 22.1 (c) Modern Bridge Design—Arrangement of Wheelhouse Equipment Based on Det Norske Veritas

TABLE 22.I Typical Deck Arrangements for Accommodation

Wheelhouse	Wheelhouse and Captain's Cabin	Wheelhouse
Captain's Deck (with Chief Engineer)	Officers Deck	Captain's Deck (with Chief Engineer)
Officers Deck	Lounge and Mess Deck	Officers Deck (with Lounge and Mess)
Lounge and Mess Deck with Galley	Crew Deck and Galley	Crews Deck (with Lounge and Mess)
Crew Deck	Stores and Workshops in Hull	Galley and Stores (Upper Deck)
Stores and Workshop Deck (Upper Deck)		Workshops in Hull

TABLE 22.II Typical Ship Design Stowage Factors

Ship Type	*Stowage Factor Range m^3/t DWT*
Bulk Carrier	1.24
Car Carrier	0.35 car/t DWT
Container Ship	0.8 TEU/t DWT
Crude Oil Tanker	1.22
Cruise	0.7 – 0.3 pass/t DWT
Cruise Ferry	0.45 – 0.37 lane m/t DWT
LNG Carrier	2.02
Ore Carrier	0.54
Orange Juice Carrier	0.74
Multipurpose Cargo	1.70
Product Tanker	1.35
Reefer	1.35
RO/RO	0.33 – 0.25 lane m/t DWT

Engineer's cabin is not on the same deck as the Captain's it should be located on the deck level below the deck officers with all the Engineers with similar arrangement to the Captain's.

The sizing of the holds, tween decks and tanks are often simply what results from the logical structural major member location or it may be a deliberate balancing of cargo quantity and handling gear to take the same time at each location. This prevents the situation where all spaces are loaded/unloaded except for one space that takes significantly longer (17).

All merchant ships are equipped with ballast tanks but the designer must assure that they are used only when the ship is either partially loaded or empty of cargo. When the ship is in the Full Load Condition it should not require any ballast. The cost of transporting non-revenue-generating ballast in the Full Load is not acceptable in a design unless beam restrictions combined with high vertical center of gravity cargo necessitates it. The designer must remember that the merchant ship is first and foremost a revenue-generating tool and any operating cost savings make the ship more productive. The most important characteristics are Deadweight (DWT), Cargo Capacity, and Fuel Consumption; DWT being the weight of cargo carried, the capacity is related to the cargo deadweight by the *Stowage Factor*. Typical stowage factors are given in Table 22.II, but the ship type chapters in Volume II should be referred to for exact values. Also it is normal for the stowage factors to reduce as ship size increases. So in the table the lower value when a range is given is for the larger ship.

The ship should be designed to have the lowest possible fuel consumption, as fuel cost today may be as much as 55-60% of annual operating cost.

Today's ballast system is, of course, segregated from all other tanks. This means only clean seawater in and out. Smaller fuel service and settling tanks are usually heated and require locations away from the normally cold shell. The designer should_also take care to avoid adjacencies of manned spaces to heated tanks.

The current focus on ballast water exchange as a way to prevent transport of foreign marine species from one area of the oceans to another must be considered in the design.

The SNAME Technical and Research Bulletin 7-3 (18) states:

> The general arrangement design is documented by the general arrangement drawings. The general arrangement drawings define design requirements that are described pictorially rather than in the written specifications. The final general arrangement drawings must reflect only those details that are required as part of the final contract package.

The General Arrangement drawings include the outboard and inboard profiles and the deck arrangement drawings. An external bow view, stern view, and top view are also sometimes included in the later stages of design. The bow should always be shown to the right. The nomenclature for the stages of ship design is that used in Chapter 5 - Ship Design Process. The General Arrangement drawings are functional design development and communication tools throughout the design process from the feasibility studies, concept and early preliminary design stages. They evolve to become more formal contractual documents beginning in preliminary design and then finally when issued as a formal product of the contract design. Typical content and details at the different design stages evolve as the purpose of the drawings changes through these stages of design as shown in Table 22.III, and in the following discussion.

Feasibility Studies: At this early stage, a typical General Arrangement might consist of sketches or simple drawings showing the arrangement of, or below, the main deck and the inboard profile. A section through the hull may also be included, particularly in commercial designs, to show hull/cargo arrangement

Concept Design (cD): In the concept design phase, the typical General Arrangement drawing includes plan views and an inboard profile. The plan views are cuts made just below the deckhead of the level of a particular deck and show the arrangement of spaces on that deck level. On a commercial design at this stage, there might only be a single plan view taken just below the main deck to show the major subdivision and space use within the hull. The inboard profile is a cut made at the ship centerline showing the arrangement just to the port side of the centerline, unless special provisions and notations are made. The arrangement might just show space blocks allocated by function rather than all the individual compartments and spaces. The drawings need to include baseline, centerline, and longitudinal coordinates and be prepared at a consistent scale throughout. t

Preliminary Design (PD): In the preliminary design phase (which may be blurred with both or either concept and contract design), the typical General Arrangement drawing includes more detail and a definition and identification of all compartments or spaces. The principal pieces of machinery might be included on the General Arrangement drawings.

Contract Design (CD): In the contract design phase, the General Arrangement drawing becomes a formal contractual document. It needs to show requirements of the design, but only those that are intended to be formally required. Some design development detail may be deleted from earlier versions and more detail may be added in other areas. Details of navigation lights, mission specific equipment, and mooring arrangements are defined.

Table 22.III has been liberally adapted from reference 12 by Professors Parsons and Lamb at the University of Michigan.

22.3 ACCOMMODATION ARRANGEMENT DESIGN

In state-of-the-art ships all crew resides in the deckhouse. The deckhouse is usually constructed in one or two blocks, pre-outfitted and lifted on to the hull (Figure 22.2). In a recent U.S. Government ship design the deckhouse configuration consisted of combinations of standard rooms of identical size. Where rankjustified more space, such as captain and chief engineer, three adjacent rooms were provided.

These were outfitted as captain's office in the center and captain's stateroom to one side and sitting room to the other side. The chief engineer's quarters were arranged likewise. Crew members were each allocated one room. When this approach is used the standard stateroom size and arrangement should be such that the prospective joiner manufacturers panel size can be used either whole or half, no slivers.

It is prudent for the designer to establish a liaison with at least two prospective joiner and furniture vendors since shipbuilders usually subcontract out the detail design and

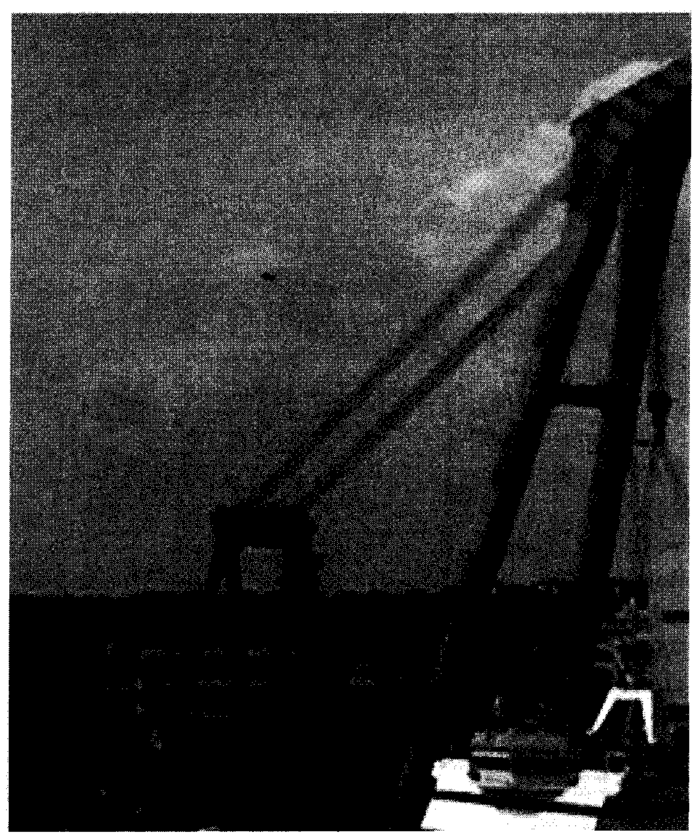


Figure 22.2 Complete Turn-key Subcontracted Deckhouse Block

TABLE 22.III Typical Details to be Shown on General Arrangement Drawings

	Plan View(s) below Main Deck or on All Decks			*Inboard Profile*			*External Views Outboard Profile, Bow, Stern, Top*		
Detail	*cD*	*PD*	*CD*	*cD*	*PD*	*CD*	*cD*	*PD*	*CD*
Baseline	x	x	x	x	x	x	x	x	—
Baseline	x	x	x	x	x	x	—	x	x
Centerline	x	x	x	x	x	x	—	x	x
Longitudinal scale bar	x	x	x	x	x	x	—	x	x
Identification of AP & FP	x	x	x	x	x	x	—	—	—
Shell	x	x	x	x	x	x	—	x	x
Decks	—	—	—	x	x	x	—	—	—
Structural bulkheads	x	x	x	x	x	x	—	—	—
Joiner bulkheads	—	—	x	—	—	x	—	—	—
Frames or frame spacing	—	x	x	—	x	x	—	—	—
Hatches	x	x	x	x	x	x	—	—	—
Arches in structure	—	x	x	—	x	x	—	x	x
Fire and watertight doors	—	—	x	—	—	x	—	—	x
Joiner doors	—	x	x	—	—	x	—	—	—
Trunks	x	x	x	x	x	x	—	—	—
Equipment removal plates	—	x	x	—	x	x	—	x	x
Major structural members	—	—	x	—	—	x	—	—	
Stanchions	—	x	x	—	x	x	—	—	x
Masts	—	—	x	—	—	x	—	—	x
Deck/platform heights	—	x	x	—	x	x	—	—	—
Sheer and camber	—	—	—	x	x	x	—	x	x
Capstans/winches	—	—	x	—	—	x	—	—	x
Chain lockers	—	x	x	x	x	x	—	—	—
Anchors	—	—	x	—	—	—	—	—	x
Compartment titles	—	—	x	—	—	x	—		
Bitts/chocks/fairleads, etc.	—	—	x	—	—	x	—	—	x
Ladders/stairs	—	—	x	—	—	x	—	—	x
Gratings	—	x	x	—	—	x	—	—	x
Antennas (Navy vessels)	—	—	—	—	—	x	—	—	x
Navigation lights	—	—	x	—	—	x	—	—	x
Mission equipment	x	x	x	x	x	x	—	x	x
Main engines/gears	—	x	x	x	x	x	—	—	—
Propellers/shafting	—	—	—	x	x	x	—	x	x
Rudder	—	—	x	x	x	x	—	x	x
Definition of tanks	x	x	x	x	x	x	—	x	x
Boats/rafts	—	x	x	x	x	x	—	x	x
Cranes/Cargo gear	—	x	x	—	x	x	—	x	x
Windows/portlights	—	—	x	—	—	x	—	—	x
Identification of major items	—	—	x	—	—	x	—	—	x
Typical cabin arrangements	—	—	x	—	—	—	—	—	—
Consistent use of line types	x	x	x	x	x	x	—	—	—
Table of principal particulars	—	—	—	x	x	x	—	—	—

Note: cD = Concept Design PD = Preliminary Design CD = Contract Design

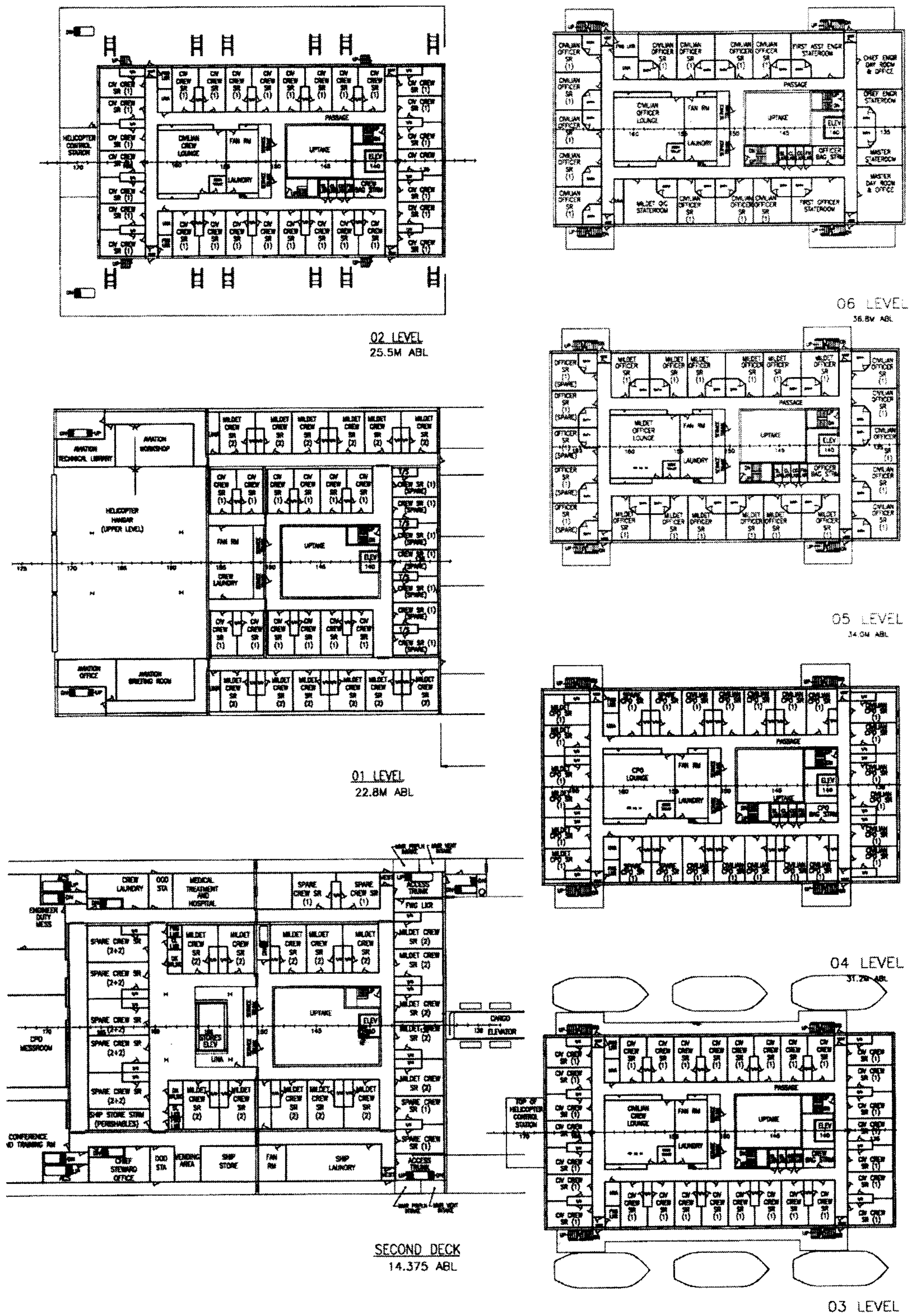


Figure 22.3 Accommodation Arrangement for a U.S. Military Sealift Command Ship

construction of this effort. Mess rooms, galley and stores are usually located in the lower tiers of the deckhouse. Ranks are segregated into different tiers and where possible lounges are provided for each rank at their stateroom locations. **In** addition to interior inclined stairway towers and exterior inclined ladder access, tall deckhouses are provided with a personnel elevator.

Figure 22.3 shows the accommodation arrangement for

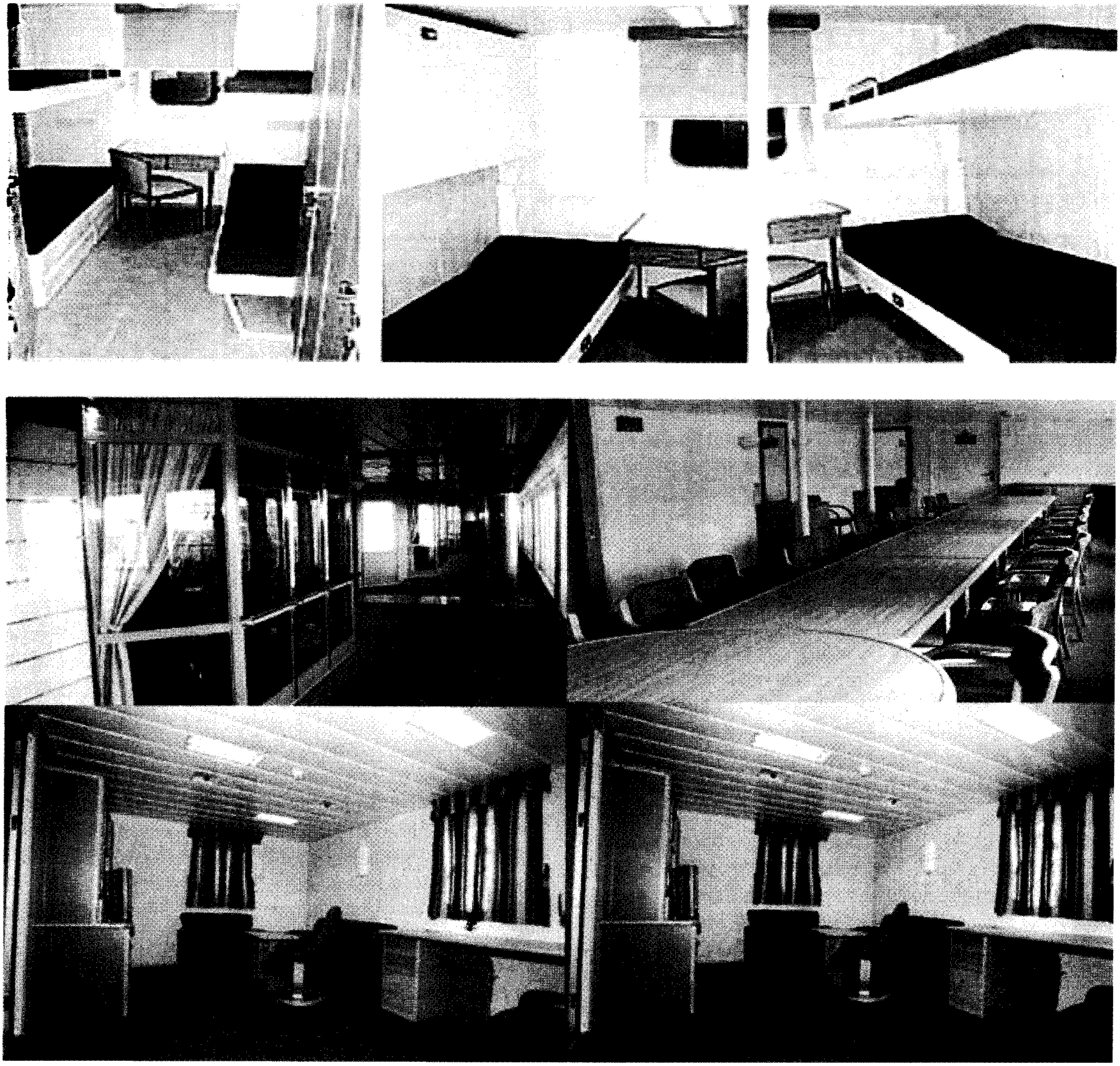


Figure 22.5 Typical Cabins and Passenger Areas on a Commercial Ship

furniture is usually a government standard sheet metal design based on providing the basic necessary amenities. They also have athwartship berths and berths on the ship/deckhouse side. Some countries prohibit the arranging of berths against the ship or deckhouse sides for commercial ships. It is also a better arrangement considering heat/cold flow from the side and for access to the window or airport. One ofthe authors can personally attest to the fact that sleeping in a berth along a deckhouse side, the side of the body nearest to the deckhouse side is hotter/colder than the side facing into the cabin depending on whether the temperature outside is hotter/colder than the cabin temperature.

The national laws state minimum clear deck areas in cabins for crew and officers, and a number of design publications give required minimum guidance areas, but today they are both usually exceeded for commercial ships. This

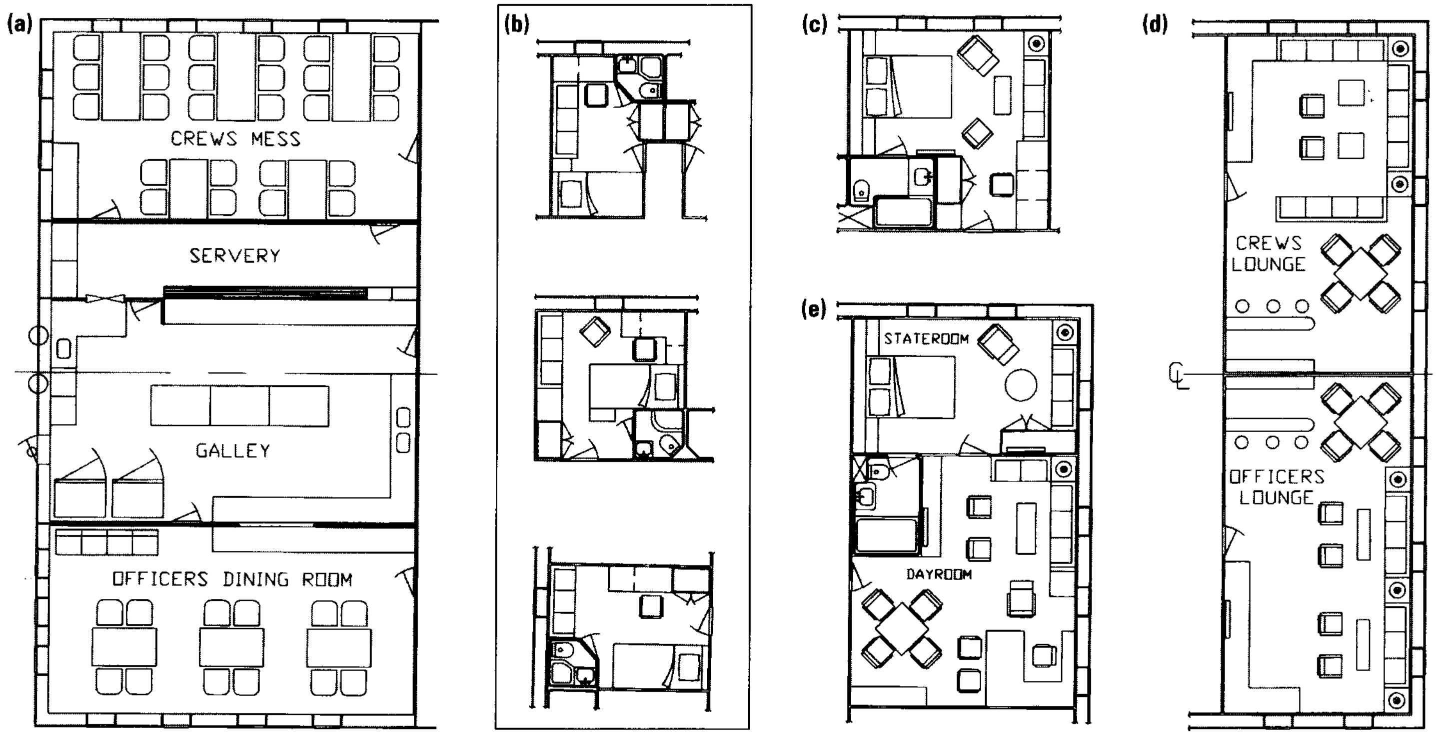


Figure 22.6 Typical Modern Commercial Ship Accommodation Arrangements. a) Dining Room, Mess Room and Galley. b) Crew Cabins. Minimum Area Arrangement (Top); Toilet Arranged Inboard (Middle); Deckhouse End Arrangement (Bottom). c) Officer's Cabin. d) Officers and Crew Lounges. e) Captain's/Chief Engineer's Accommodation.

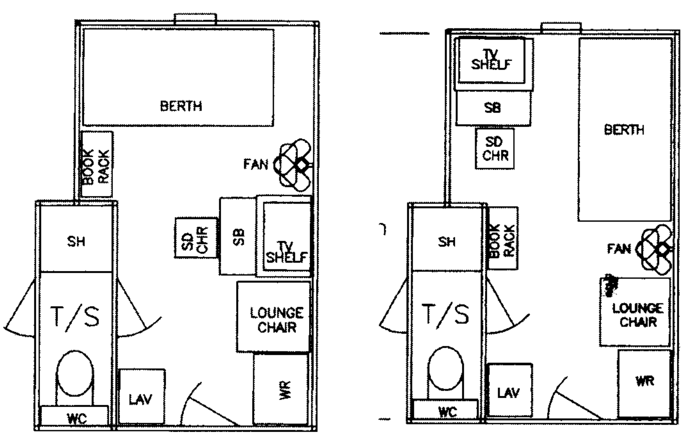


Figure 22.7 Typical Recent U.S. Government Ship Accommodation Arrangements

is because it is necessary to provide superior amenities on board ships in order to attract people to a life at sea and satisfy Union Agreements.

So rather than try to design to the minimum areas it is better to design arrangements in accordance with today's best practice.

Note that on some container ships the usual built-in dry and refrigerated storerooms are being replaced with dry and refrigerated containers that are located adjacent to the galley. The obvious advantage of this arrangement is that the stores can be loaded as quickly as any other container.

An effective arrangement for integrating the stairway and elevator and providing a service access trunk is shown in Figure 22.8. Special care is required to ensure that each space; stairway, elevator trunk and service trunk, are each surrounded by the regulatory specified fire bulkheads and that the doors to each space are fire doors.

Officers and passengers commonly share a dining room or saloon equipped with tables, chairs, and sideboards. The crew mess is likewise provided with tables, chairs, sideboard, and a drinking fountain. Various small appliances such as a coffee maker, a 2-bumer warming unit, a toaster and a small refrigerator are provided for use when the pantry/servery is closed.

Integral with the accommodation spaces are control rooms such as the wheelhouse, machinery and cargo control centers. These are the main spaces in which the ship's crew works, so they spend a lot of time in them. All these spaces focus on *human factors* to develop the best man-machine interface and to try and assist in the increasing amount of information that is available to the crew. Today wheelhouses are being designed for one-man operation and machinery control centers are being designed for unmanned engine rooms. The wheelhouses of today's ships have al-

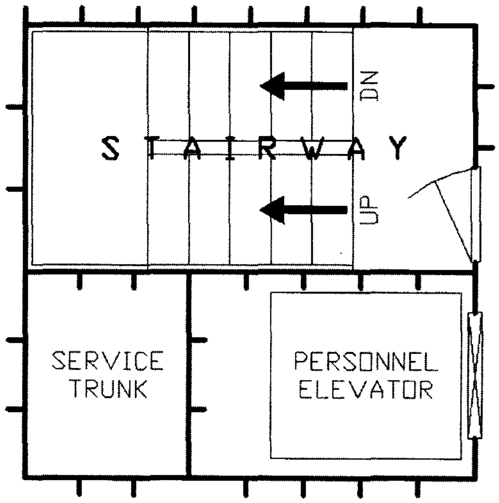


Figure 22.8 Stairway, Elevator and Service Access Trunk Arrangement

most duplicate machinery control consoles as found in machinery control centers, excluding the switchboards. The classification societies have special rules for Bridge design, and each of the major wheelhouse equipment/controls suppliers have studied the ideal arrangement for the wheelhouse. The perimeter shape of the wheelhouse has changed to improve the capability of reduced manning on the bridge to function efficiently. The arrangement of the wheelhouse windows to reduce parallax distortion as shown in Figure 22.3(c) is just one example. On some ships there is no longer a steering wheel, being replaced by a joystick.

The ship general arrangement designer should recognize that this aspect of the accommodation design is specialized and should work with the equipment/controls supplier to design the best bridge for the ship taking into account its service, manning scenario and system to be installed. ""

22.4 CLOSURES

22.4.1 General

For commercial ships, closures to openings in the main hull, deck houses, tanks, subdivision bulkheads, and elsewhere affecting the safety of the ship, or persons aboard, are subject to the regulations of the International Maritime Organization (IMO) which are administered by country of Registry Regulatory Body (in the U.S. it is the U.S. Coast Guard), and classification society with which the ship is classed.

The applicable standards of construction are adequately described in these regulations and thus will not be duplicated here, but individual details may be highlighted. However, the sketches and descriptive material which follow are representative of standard practice in accordance with the regulatory bodies as applicable to most commercial ships.

Requirements for closures may be divided into two general categories:

1. closures which are routinely opened and closed while at sea, such as access and escape doors in accommodation and work spaces, and
2. cargo space closures including hatch covers, sideports, sluice gates, conveyor belt gates, etc., which normally remain secured while at sea.

22.4.1.1 Closures operated while at sea

These doors, hatches, scuttles and manholes are designed to the requirements of regulatory bodies and the classification societies, of strength equivalent to the surrounding structure. Class 1 hinged doors are fitted above the bulkhead deck. Sill heights and coaming heights are prescribed in the International Load Line Convention and in the classification society rules. Sliding watertight doors, Class 2 or 3, are fitted in subdivision bulkheads below the bulkhead deck only where unavoidable. These sliding watertight doors are usually found in machinery and steering gear room bulkheads. They require an open/closed indicator on the bridge, as well as remote closing control.

22.4.1.2 Closures secured while at sea

Cargo hatches, sideports, and RO/RO bulkhead doors, must meet regulatory body subdivision requirements and must be classed as closures in a watertight bulkhead. Thus, gasketing and dogging must be designed to provide a watertight seal under a head of water, the same as for bulkheads. The only instances where absolute watertight requirements are not strictly followed are in the case of tanker free-flow sluice gates which are Drop Tight, Class 2 and Class 3 sliding doors and watertight conveyor gates on self-unloading vessels, which are built to specified leakage limitation requirements. Even though not strictly classified as watertight, owners and regulatory bodies, now favor use of conveyor-belt doors, which are designed to reduce the maximum leakage when closed and secured around the rubber conveyor belts to approximately 25 percent of the capacity of the bilge system serving the flooded compartments.

2.4.2. Watertight Doors

Watertight doors include those required for personnel access on weather decks and through watertight bulkheads, and those required to move cargo into or out of a ship.

2.4.2.1. Oeckhouse access

Hinged watertight metal doors are fitted at all exterior deckhouse openings on the weather deck level as required by the regulatory bodies for the particular ship and service. These types of doors are fitted with a neoprene type gasket and secured with suitably spaced individual, or gang (quick acting) hand-operated dogs, which may be manipulated from either side of the door (Figure 22.9). They have a certain minimum sill height depending on the space protected, the height above the assigned load waterline, and distance from the bow.

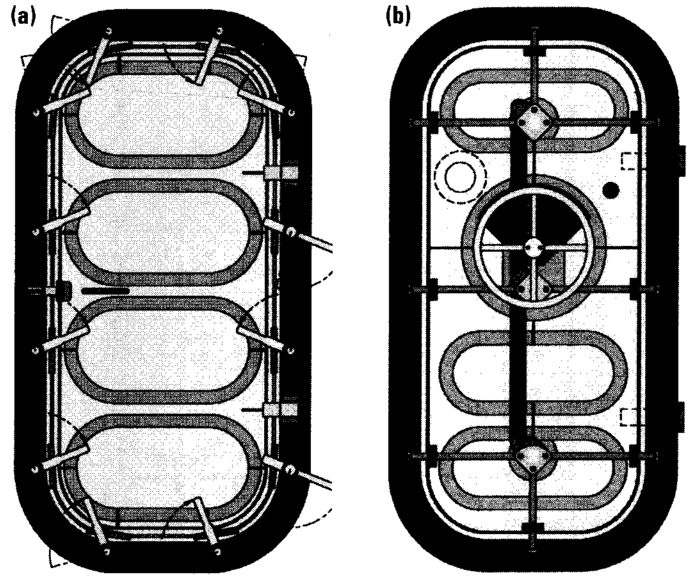


Figure 22.9 Hinged Watertight Doors. a) Dogged Watertight Door, and b) Quick Acting Watertight Door.

2.4.2.2. Watertight bulkhead access

Watertight doors also are fitted in subdivision bulkheads below the ship's bulkhead deck. The number, location, and method of closing such doors are determined by the regulatory bodies in accordance with the characteristics, number of passengers, and service of the ship.

Figure 22.10 shows a mechanically operated, sliding watertight door which must be used in place of a hinged door, when the door sill is less than the prescribed distance above the subdivision load line, or when the size of the opening is too large to make a hinged door practicable. If a remote controlled door, located in the lower part of the ship, is to be opened while at sea, the sliding watertight door is mandatory. The most common case is a door from the machinery space to the shaft alley or other adjacent space. The door must be operated remotely, locally and from above the bulkhead deck with open/closed indicators in the wheelhouse.

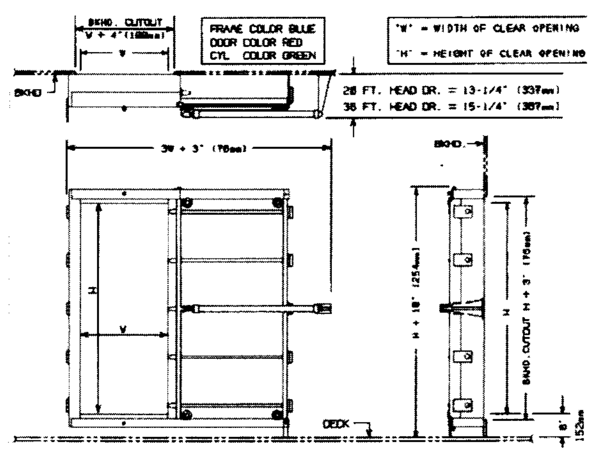


Figure 22.10 Mechanically Operated Sliding Watertight Door

22.4.2.3 Sideport access, stores, and fueling doors

Sideports are also used to provide access to a cargo hold, personnel or vehicle embarkation, and stores spaces where overhead access cannot be fitted conveniently. Fueling doors have been the cause of some RO/RO ship accidents and fueling access is now from the deck above. All side ports are required to be located above the deepest subdivision load line and watertight. Sideports doors can swing either inboard or outboard.

Sideports ordinarily are fitted at the upper twecl\deck level. Cargo is run through the port by forklift truck, conveyor, or other means and then lowered to the decks below by elevator, vertical conveyor, or a hoist acting through a hatch opening. As a general rule, the type of cargo thus handled is limited to small packaged units (pallets) such as canned goods and refrigerated cargo, easily moved on conveyors.

Construction in way of a side port opening must be the equivalent of the adjacent ship side structure. Thus the opening in the shell must be adequately compensated, by heavier structure, as required by the classification society.

Figure 22.11 shows a hydraulically operated inboard swinging sideport door including the closely spaced dogs, which force the door against a gasket making a watertight seal.

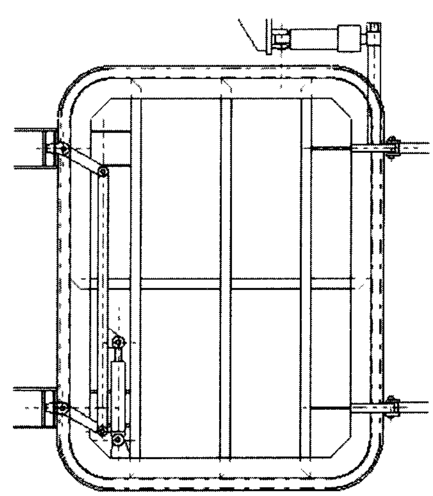


Figure 22.11 Hinged Cargo Loading Sideport

Recessed sideports, which swing inboard, are less vulnerable to damage from docks, or barges tied alongside, but must be reinforced with strong backs in addition to dogs. Hinged sideports up to approximately 1.2 m width are built in one section; wider openings are generally fitted with articulated hinges that swing the door open parallel to the shell. Double doors are infrequently used due to sealing problems. Other variations in sideport construction particularly for large-size openings include horizontal and vertical sliding power-operated doors. Such doors are frequently used in RO/ROs where door size and deck space limitations often do not permit use of swinging hinged doors.

22.4.2.4 Cargo stern ramps and doors

On RO/RO ships, ferries, and military vehicle carriers with stem ramps, a stem loading door is usually fitted, off center or at the centerline of ship through a flat, transom stem. The stem door is usually the primary loading/offloading facility for RO/RO ships.

Stem doors generally are hinged up above the loading deck level but sometimes the door and the ramp are combined and so they hinge down, and are secured againstneoprene gaskets around the boundaries of the stem opening to form a watertight closure.

The raising and lowering of the stem door is normally accomplished by hydraulic cylinders actuated by controls suitably located at the stem. Since stem doors must withstand the impact of seas, they tend to become rather massive structures.

Figure 22.12 shows a typical stem ramp and door arrangements.

22.4.2.5 Bow doors

Bow doors are fitted on ferries to simplify the loading and unloading operations. The door is often part of a system consisting of side hinged bow doors or a hinged bow visor,

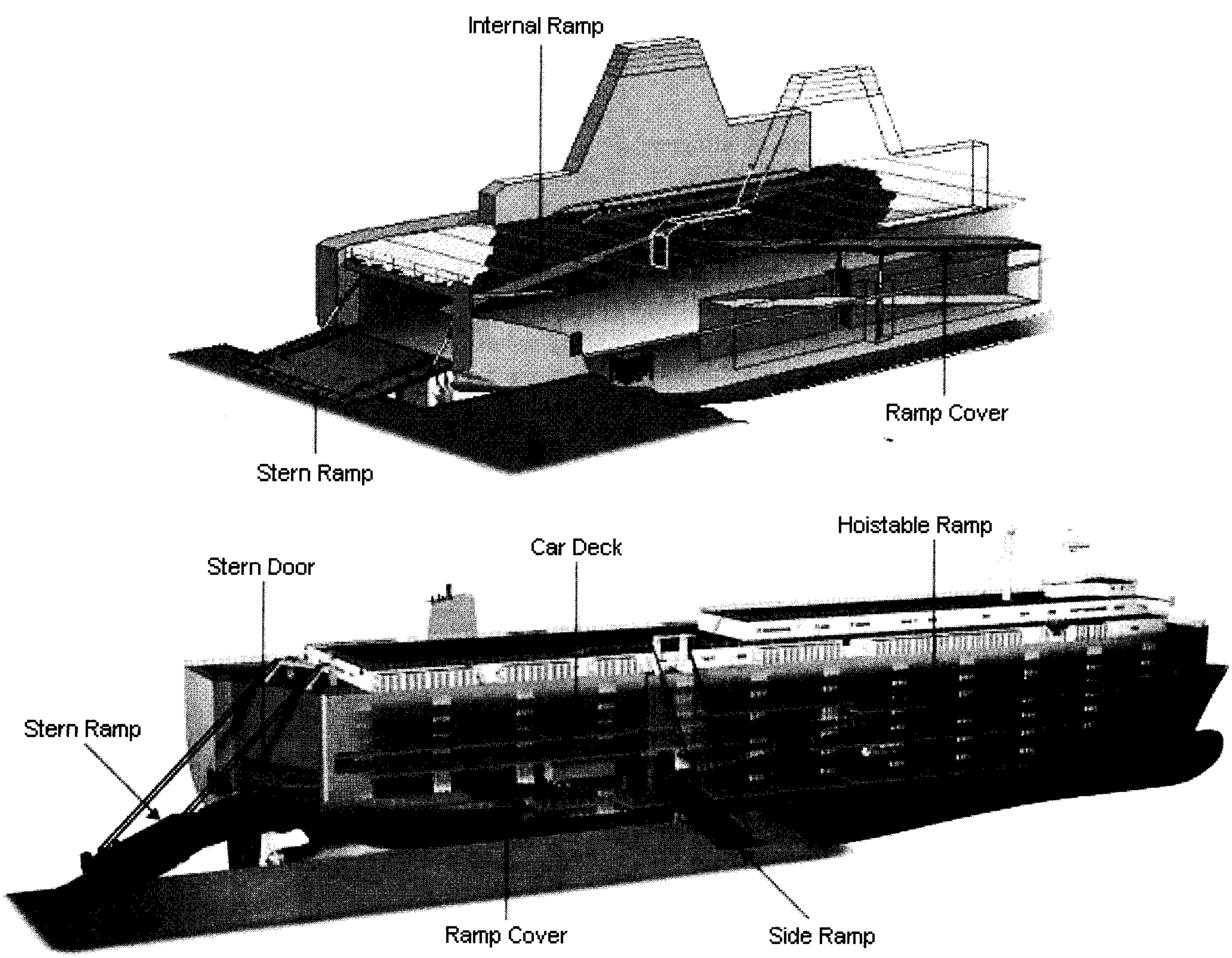


Figure 22.12 Typical Stern Watertight Doors and Ramps

with another watertight door inside and aft of the bow as shown in Figure 22.13. Figure 22.14 shows an arrangement with a bow visor.

22.4.3 Miscellaneous Type Doors

Miscellaneous type doors include gastight, weathertight, and non-watertight doors.

22.4.3.1 Gastight doors

Gastight doors are of lighter construction (similar to weathertight doors) but must meet more exacting tests for tightness than watertight doors, and are usually limited to the hinged type suitable for installation in the boundary bulkheads of a space containing hazardous or objectionable fumes, such as a battery and sewage treatment room.

22.4.3.2 Weathertight doors

Weathertight doors may be fitted at exposed deckhouse openings where a watertight door is not required by regulations. Such doors usually consist of steel or aluminum, so built and drained as to exclude driving rain and spray, and capable of withstanding the impact of a boarding sea (Figure 22.15).

A fixed light should be provided in all doors opening to the weather deck. Hinged doors are most commonly used but sliding doors are often used for wheelhouse sides, as they are effortless to open against wind and weather. The openings into deckhouses are often recessed inboard of the house side for protection from the weather, and to avoid obstructing the passageway when open. Hinged exterior doors always should be fitted with the hinges on the forward, outboard side so that wind or sea striking the door will tend to close it.

Today, steel or aluminum doors with painted fitlsh are more frequently used in lieu of wood doors. They perform the same function and meet the same general requirements as wood doors and require less maintenance. They are either similar in construction to steel watertight doors, but of somewhat lighter construction, or are of double-skin insulated designs. Both have fewer securing dogs. Stainless steel doors are easier to maintain than ordinary steel doors, but are considerably more expensive. On ships with open bridge wings, stainless steel sliding doors are used since their opening is not affected by wind. These doors have large windows the same size as wheelhouse windows and with the doors in the open position the door windows line up with the wheelhouse windows for proper visibility.

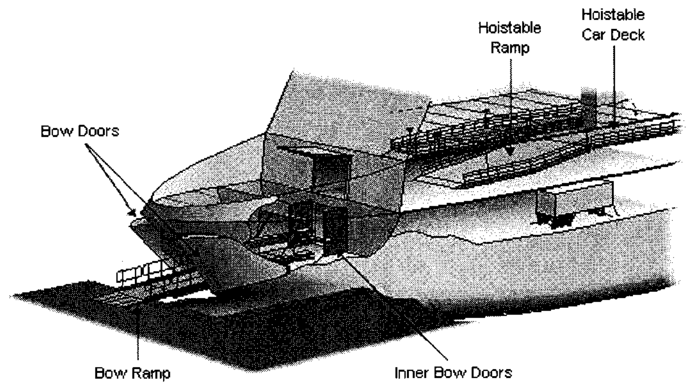


Figure 22.13 Bow Door Arrangement

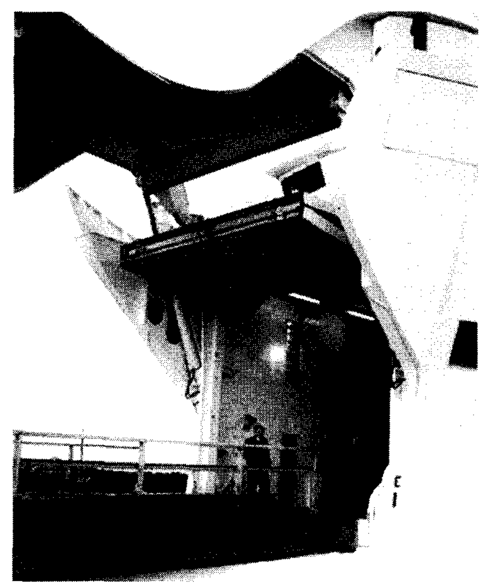


Figure 22.14 Typical Bow Door and Visor

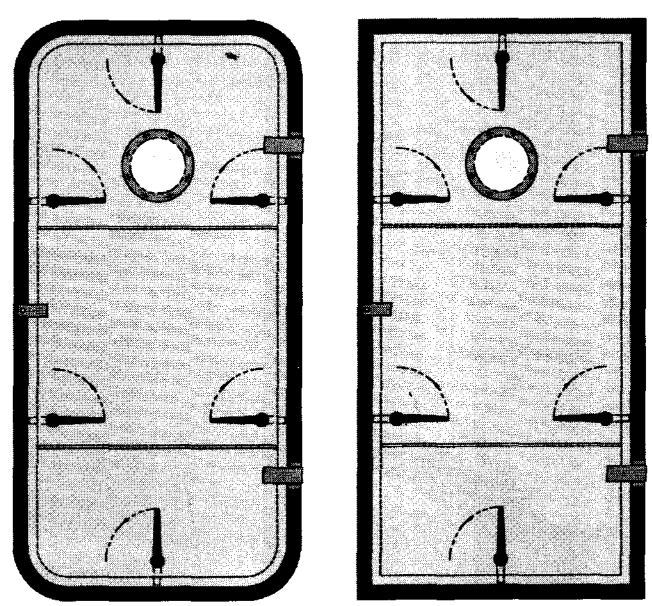


Figure 22.15 Weathertight Doors

22.4.3.3 Non-watertight steel doors for stores and shops

Non-watertight doors of dished construction or made up of a 5-7 mm thick plate, suitably stiffened, and installed at entrances to stores spaces and working areas. Either type of door can be secured with a padlock rather than a rim lock.

22.4.3.4 Non-watertight joiner doors for accommodations

Metal joiner doors are used extensively for staterooms, sanitary spaces, and living quarters where fire-protection regulations prohibit the use of joiner wood doors. Such doors are formed of light gauge sheet steel and are specially insulated for soundproofing, to prevent drumming, and to meet fire resistance requirements. Kick-out panels in the lower part of the door often are arranged as ventilation louvers. Magnetic holdback and self-closing devices are used on passageway fire doors, remote controlled where required by the rules for fire control. Door hardware should be of substantial steel or bronze construction.

22.4.4 Windows, Airports, and Fixed Lights

Rectangular windows with cast or extruded bronze or aluminum frames with steel retaining clips are usually fitted in lieu of airports, in the upper levels of a superstructure, and the wheelhouse. In the wheelhouse they are fitted with wire-inserted heat-treated plate glass, at least 6 mm thick for protection. The glass may be tinted to exclude solar glare in all locations except the wheelhouse. The sliding windows descend vertically into a metal pocket or drain pan below the window and the pan is drained to the exterior. Two or more of the front windows in the wheelhouse are usually fitted with wipers, and/or rotating disc inserts know as clear views, for visibility in rain or snow.

Wheelhouse windows are canted out at the top to provide protection from sun glare, as well as avoid parallax distortion when looking down over the bow. Typical windows are shown in Figure 22.16, and airports and fixed lights in Figure 22.17.

Large view windows in passenger vessels in lake, bay and sound service are commonly fitted with double pane windows with an air space to minimize heat loss.

Hinged airports, complete with air scoops and screens, are fitted in superstructures and lower levels of deckhouses. In the past, above the main deck, the passengers or crew could open airports at will. However, today most accommodation spaces are air-conditioned so fixed lights or fixed windows are fitted.

Airports and fixed lights generally have frames constructed of cast bronze or aluminum fitted with steel retaining clips. They are fitted with plate glass at least 6 mm thick, heat treated in exposed locations on seagoing vessels, and of regular glass on inland vessels in locations and on runs where there is no danger of water impact from the seas.

Deadlight covers are made of cast bronze, aluminum, or steel; they hinge upward and inboard, in which position they are secured with a keep chain.

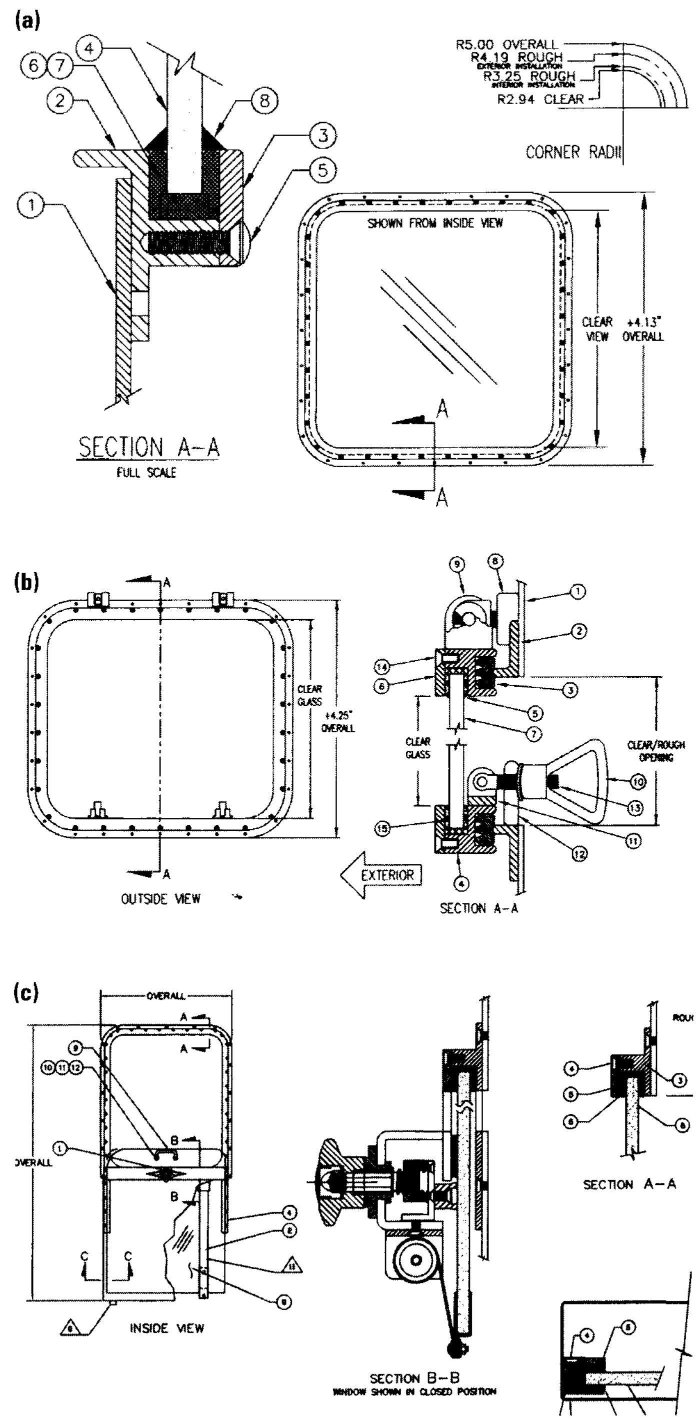


Figure 22.16 Typical Marine Windows. a) Fixed Window. b) Opening Hinged Window. c) Vertically Sliding Window.

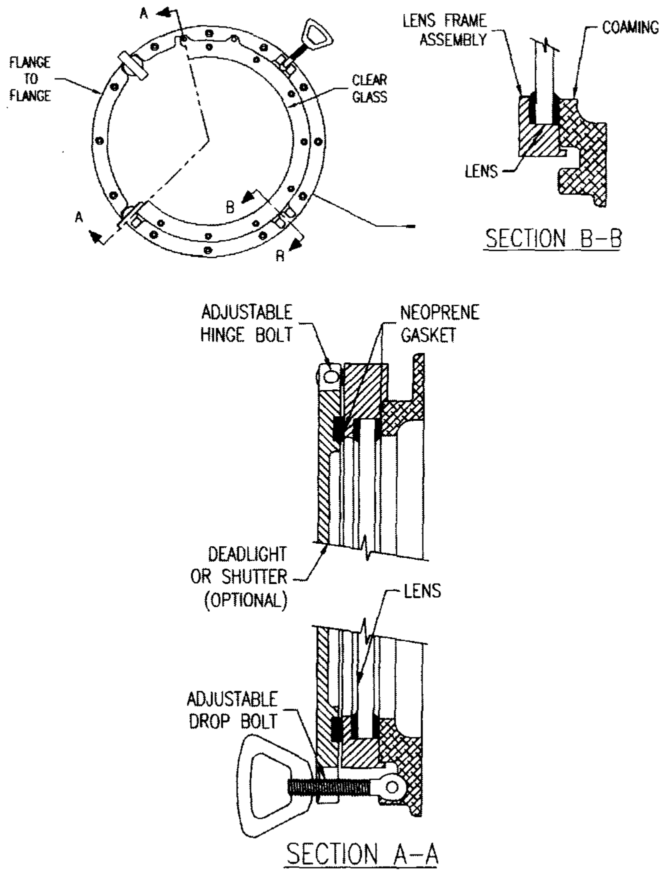


Figure 2.17 Typical Airports and Fixed Lights

Eyebrows are fitted over opening windows and airports on the outside of the hull and deckhouses to drain water away from the opening. If the airports spigots project at least 19 mm past the shell, eyebrows may be omitted. Drip pans, with exterior drains, are provided under opening windows and airpo~.

Any portlight having a sill below a line 2.5% ofthe~eam above the deepest subdivision load line must be fitted as a fixed light (Current USCG Rules).

22.4.5 Companionways, Access Hatches, and Manholes

Companionways are used to provide a sheltered landing when the space below is reached by means of an inclined ladder or stairway from a weather deck. A hinged watertight steel door with a 460 or 61O-mm sill and a fixed light, is standard for a weather deck companionway. Full headroom is provided over the landing inside the companionway.

Hatches are fitted on weather decks over boson's stores, workspaces, steering gear, and other spaces where access from the weather deck is essential and/or entrance cannot be made conveniently from below deck. For ease of operation the covers of access hatches, if frequently used, are generally fitted with counterbalance weights or springs with hold-back hooks to prevent them from closing accidentally and injuring personnel. The covers (Figure 22.18) are constru'ited of steel plate, fitted with dogs and resilient gaskets. Weather deck hatch coarnings are 610 mm high or less, depending upon the location, as specified in the IMO regulations.

Manholes are fitted where infrequent access to tanks, cofferdams, and void spaces is required. To insure two means of escape and to facilitate ventilation, it is standard practice to provide two manholes to each tank or void space, located at diagonally opposite corners, but for relatively small spaces one manhole is acceptable.

Manholes are either oblong or round depending upon the adjacent stiffener spacing and the configuration of the space available for the installation. The covers are bolted down on resilient gaskets for access to small ballast tanks and other spaces, where required to be watertight. Neoprene gaskets are used for oil-tight applications. The minimum clear opening for a round hole should not be less than 460 mm or oblong holes 580 by 380 mm. These dimensions were established by the U.S. Admeasurement Rules. Today, with all international trading ships, the admeasurement follows the 1970 International Tonnage Regulations developed by IMO; so larger holes can and should be fitted.

The only ships that need to maintain such small openings are those operating within the coastal waters of a country serving only domestic trade, which can still be admeasured using the country's old Admeasurement Regulations. For all modern ocean-going commercial ships the openings can be whatever the operations require. For example the International Tanker Association recommends that openings into tanks be suitable for passage of injured personnel on stretchers.

Manholes can be flush, raised, recessed or hinged. Typical manhole covers are shown in Figure 22.19 and consist of flat steel plates secured with bolts or studs.

Portable manhole guards, made of 6 to 10 mm plate, are fitted over manholes in cargo holds, workspaces, etc., where the cover might be damaged, and are secured by bolts or studs.

Freeing ports are provided in bulwarks to rapidly drain the enclosed deck areas of green water. The ports consist of rectangular openings 150 to 200 mm high by 600 to 1200 mm long, to fit the frame spacing in the bulwark plating at deck level. Vertical guard bars or top outboard-hinged cover plates are usually fitted. The ends of the freeing ports have a radius shape equal to the height.

Rope scuttles are fitted through the weather deck on ships where a stores hatch to the stowage space below is not available or is not suitably located for passage of heavy mooring lines. The construction of a rope scuttle is basically similar to a hinged raised manhole, as discussed previously, except that it need only to be large enough to permit easy passage of a steel or fiber rope-end eye splice. Also, the inside surfaces of the coaming are rounded to ease the passage of ropes as well as to avoid damaging them. To facilitate passing heavy wire ropes, rollers are frequently fitted inside the scuttle coaming, similar to a roller chock.

22.4.6 Miscellaneous Hull Opening Closures

Through-hull mooring ports are watertight closures in the shell plating, used in mooring arrangements where the mooring winches are located below the weather deck or where the weather deck would be too high, in relation to the mooring bitts on the pier, to afford a proper slope to mooring lines below the horizontal.

Through-hull mooring ports are of generally similar construction to the rope deck scuttles described previously, but hinge inboard and are dogged tight against a gasket from the inside. Heavy roller fairleads are built integral with the port opening since the mooring lines are lead through the opening, directly to the mooring winches.

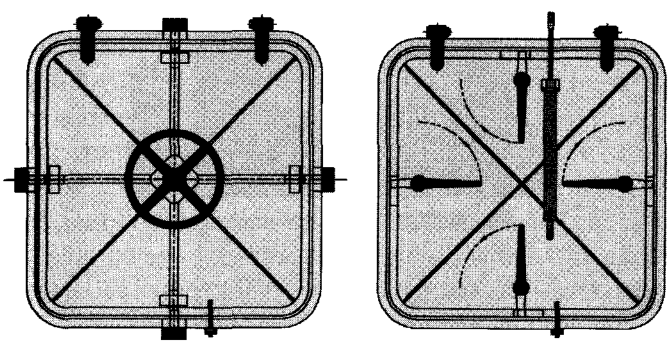


Figure 22.18 Watertight Hinged Hatches

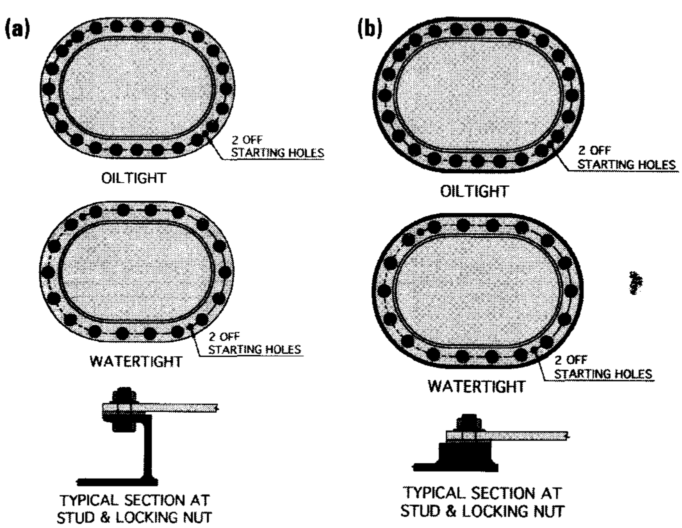


Figure 22.19 Typical Manhole Covers. a) Raised Manhole Cover, and b) Flush Manhole Cover.

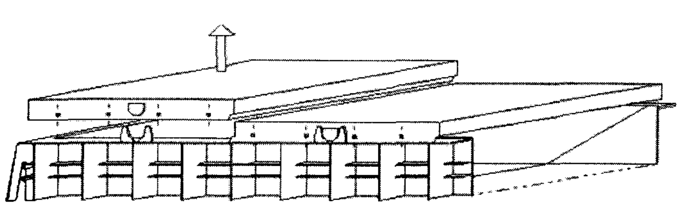


Figure 22.20 Steel Pontoon Lift-off Hatch Covers

22.4.7 Cargo Hatch Covers

Today the use of wood or steel cargo hatch covers that need to be covered by tarpaulin sheets, battened and dogged around the edges has become extinct. Hatch covers on modem vessels generally consist of a variety of types such as single-piece lift-off pontoons, hinged pontoon sections which fold to the open position, rolling covers, (fore and aft or athwartship), and cover sections which stow on a drum. In all cases the covers are made weathertight by dogging with gasketing against a usually stainless steel hatch coaming seal bar.

22.4.7.1 Single-piece pontoon covers

Pontoon covers for containerships and modem break-bulk cargo ships usually consist of large steel sections of sufficient size to cover the entire hatch opening in one piece. The pontoon is open on the under side and is designed to take the span of the hatch width without the aid of auxiliary beam supports. Lifting fittings are attached to each pontoon, which is then handled by ship, or shore cranes.

Large, single-piece pontoon covers are preferred aboard container and heavy-lift ships where special crane facilities are available for handling large units. In both cases, opened cover sections are stowed on top of adjacent or nearby hatches which need not be worked simultaneously with cargo gear or alongside on the pier. Containership pontoon hatch covers are equipped with lift fittings simulating the container comer fittings to permit the spreader on the container crane to lift the covers without the need of any special attachment. These containership pontoon covers are usually weight limited to the gross weight of the 40-foot containers, namely 30 tonnes. Lift-off covers are generally similar to that of the steel pontoon cover shown in Figure 22.20.

22.4.7.2 Mechanical covers

Mechanically operated hatch covers are oftwo basic types; those used on weather decks which are weathertight and either mounted on raised coamings or flush with the weather deck, and those used on lower decks which are non-weathertight and flush with the surrounding deck area. Typical mechanical hatch covers are illustrated in Figure 22.21. This type of cover is fitted with natural or synthetic rubber gasketing, cross joint wedges at the panel joints and quick acting dogs around all sides to attain a weathertight seal. Automatic mechanical dogging mechanisms are frequently built so as to be integral with the hatch closing mechanism on large hatch covers, thus eliminating manual dogging.

22.4.7.3 Rolling covers

End or side-rolling hatch covers, of similar construction, are usually arranged to split at the center, with half-rolling to each side or end of the hatch on permanently fitted wheels and rails. After undogging, but before rolling, the covers must be raised by special jacking mechanisms built into the cover or coamings, or by portable hand jacks, in order to clear the gasketing from the seal bar on the hatch coaming. The cover is then rolled to its stowage location, as shown in Figure 22.22. Because of the large deck areas occupied by the cover when the hatches are open, the side and end rolling covers are normally fitted only on dry bulk and Ore-Bulk-Oil carriers (OBO).

22.4.7.4 Hinged and folding covers

Ships handling break-bulk general cargo or (;ontainerized cargo, frequently have hinged, power-actuated steel hatch covers in order to obtain fast economic operation (Figure 22.23).

Weather deck hatch covers of this type are constructed with integral gasketing at all cross-joints and the periphery, which makes a weathertight seal when the covers are in position and dogged down. Tweendeck hatch covers are not required to be weathertight, thus have no gasketing, and are fitted flush with surrounding deck area to facilitate v~hicle handling and the use of forklift trucks for moving cargo to and from the hatch square and wings of the hold.

Hinged, folding hatch cover installations are made up in a multiple number of panels. The number of panels is dependent upon the length of hatch opening and the horizontal and vertical clearance at hatch ends in which to accommodate the cover panels when stowed in the open position.

Cover-actuating mechanism: Hinged folding hatch covers externally mounted on the ship's decks orcoamings, are actuated by hydraulically powered mechanisms accommodated within the hatch covers. The former are driven by one or more electro-hydraulic power stations either centrally located or near the respective hatchways.

In order to minimize the installation of hydraulic interconnecting piping aboard ship, compact built-in electro-hydraulic power units are sometimes fitted within the hatch covers. Hydraulic control stations are usually located on

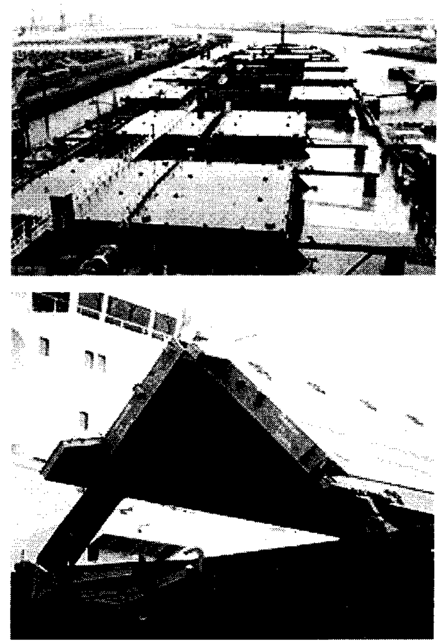
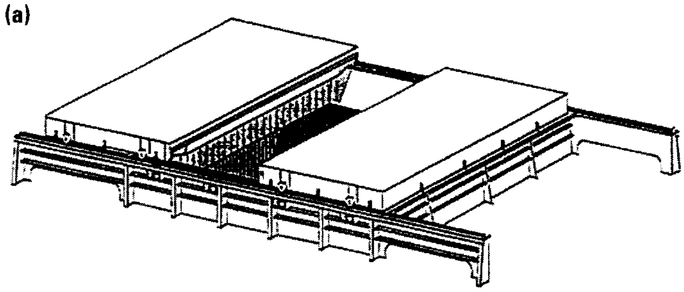


Figure 22.21 Mechanical Hatch Cover

(a)



(b)

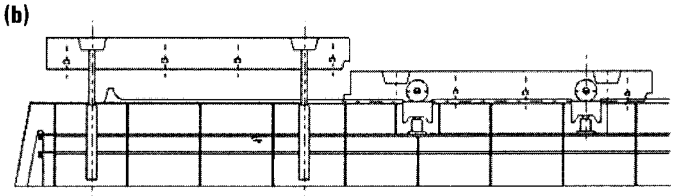


Figure 22.22 Rolling Hatch Covers. a) Side Rolling Covers, and b) Lift and Roll Covers.

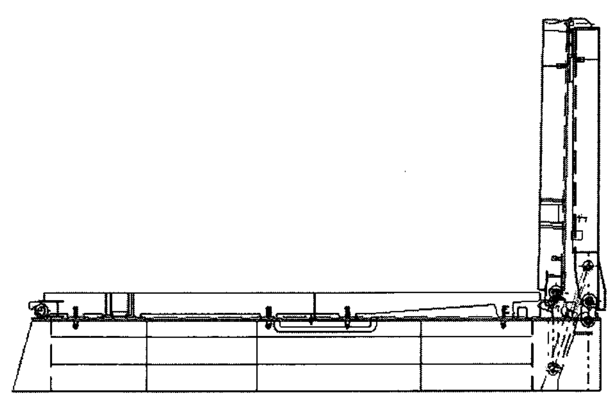


Figure 22.23 Hinged Folding Hatch Cover

winch platforms and frequently on each deck level to provide the operator with a clear view of each hatch cover during operation. As might be expected, the hinged folding hatch covers are generally more expensive than the single-piece types previously described. Hydraulically powered multi-leaf covers are more expensive than non-hydraulically powered types, but are preferred by ship operators for their ease, flexibility, and convenience of operation. Mechanical dogging devices make the closing and opening of these hatches entirely automatic in operation.

22.4.7.5 Single pull cover

Single pull covers for weather deck hatchways consist of multiple, interlocking, gasketed, rolling sections, which by application of a continuous pull from a wire rope or driven electro/hydraulically by chain are readily drawn to one or both ends of the hatch, where they disengage and tilt to a vertical position and stow compactly on a rack (Figure 22.24). Closing action follows a reverse sequence. The primary advantages of this type of cover are speed of opening and closing, plus the unlimited length of hatch to which they can be applied. As in the case of end and side-rolling covers, they must be jacked off the coaming gasket before rolling.

More sequenced operations and external mechanisms are, therefore, required than is the case with hinged folding covers, but this installation is, in most instances less expensive than hydraulic folding covers.

22.4.7.6 Drum stowing covers

Hatch covers, which stow in the open position on a drum, at either the fore/aft end or port/starboard side of the hatch opening, can be fitted to ships or barges. They can be fitted for weathertight service. The undogging/uncleating from the closed to open position and dogging/cleating from the open to closed position is accomplished automaticall'with the opening/closing operation (Figure 22.25).

22.4.7.7 Watertight, oiltight, and special type cover

Small watertight or oiltight cargo hatch covers are fitted at hatch openings of holds, which are used alternatively for dry and liquid cargo, or water ballast. To withstand the internal pressure, such hatch covers are fitted with synthetic rubber gaskets and the securing bolts are more closely spaced than typical for weather deck weathertight hatches.

In the past, tonnage regulations prescribed the maximum size of hatch openings in ballast tanks, which are exempted from tonnage measurement, but this has been overcome by the 1970 International Tonnage regulations.

On tankers and OBOs a larger oiltight hatch is generally permitted as shown in Figure 22.26. Various types of patented oiltight and watertight hatch covers are in use.

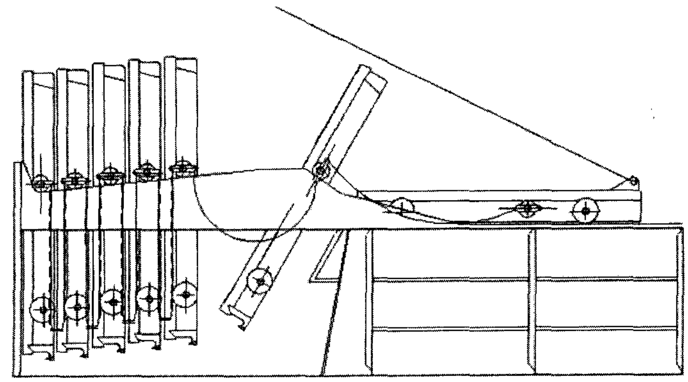


Figure 22.24 Single Pull Hatch Covers

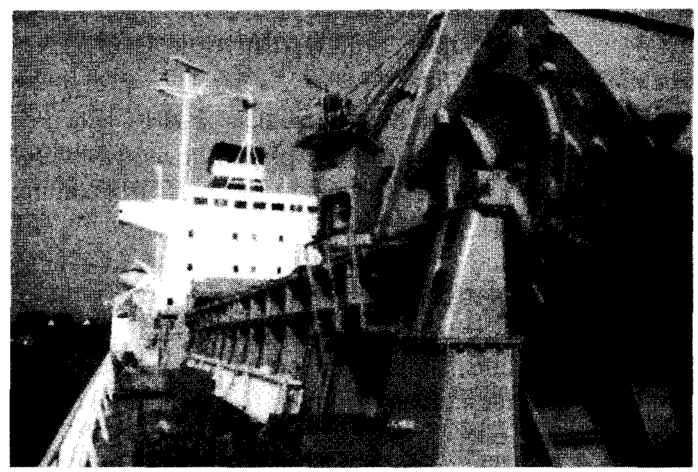


Figure 22.25 Drum Stowage Hatch Covers

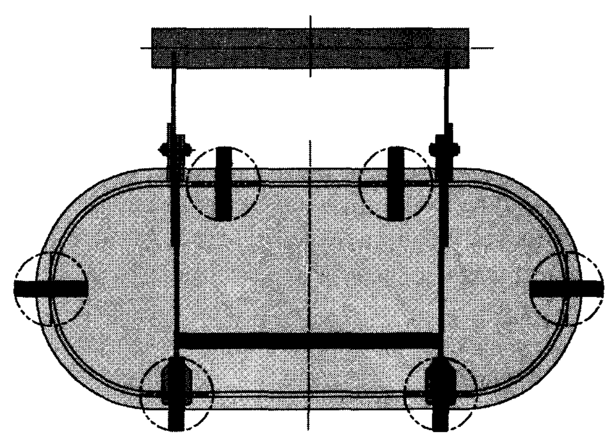


Figure 22.26 Typical Cargo Oil Hatch

22.4.8 Ventilation System Terminals

Weather deck ventilation fittings, or terminals, are used to provide a ship with adequate air intakes and discharges, suitably located and protected from boarding seas. All ventilators are provided with wire-mesh screens for protection against insects and rats. The vent terminal openings for oil tanks must be fitted with fire screens. Ventilation fittings are generally constructed of welded steel and are of sufficient strength to withstand normal shipboard wear and tear, plus corrosion due to exposure to the elements. Steel parts are usually galvanized after assembly. The height and support of coamings as well as the closing arrangements must be approved as a condition of the ship's freeboard assignment.

22.4.8.1 Cowls

Cowls are used for natural air supply to and exhaust from cargo holds or storage spaces, not fitted with a mechanical ventilation system. A cowl can be turned into or away from the wind, as required to provide a positive means of supply or exhaust.

The cowl head is fitted with a weathertight damper, which can be closed during bad weather. With the increased use of mechanical ventilation this type of terminal is becoming obsolete, and is seen only on small vessels.

22.4.8.2 Goosenecks

Goosenecks can be used for both natural and mechanical ventilating systems, supply or exhaust. They are used for venting spaces rather than ventilation and can be provided with watertight covers, secured by dogs.

22.4.8.3 Mushrooms

The standard mushroom can be used for either natural or mechanical supply or exhaust terminals. This type provides adequate protection against rain but should not be used where exposed to boarding seas, since it is not feasible to incorporate a watertight closure in its design.

The screw-down type of mushroom (bucket type) isltsed exclusively for ventilating small compartments and can be used in exposed locations. Watertight features are provided by means of screw-down-type top, operated above and below deck.

22.4.8.4 Louvers

Louvers may be used for air supply intakes for all types of ventilation systems. They are installed in weather bulkheads and provide protection from rain, but must be restricted to protected locations, not vulnerable to seas. They are generally used for large- volume systems, such as the engine room ventilation, are of sturdy construction, consisting of frame and louver blades set at about 45 deg with 50 mm (2 in.) openings, and are provided with wire-mesh screens. It is advisable to construct louvers of non-corrosive materials and design them to be removable, since experience indicates that louvers must be replaced several times during the life span of the ship.

Ventilation ducts or openings penetrating subdivis,ion bulkheads below the Margin Line must be fitted with watertight closure devices, operable from above the Margin Line, and must be provided in accordance with USCG requirements.

22.4.8.5 Air lifts

Air lifts are used in place of louvers at points on deck exposed to seas. They consist essentially of a steel box with a central baffle plate over which the stream of air must pass. Any water entering the box is excluded by the baffle plate and drained out of the box back onto the open deck.

22.5 ANCHOR AND MOORING ARRANGEMENTS AND DECK FITTINGS

22.5.1 General

The term deck fittings, includes a broad assortment of items consisting of structure and hardware, attached to the hull, normally on the weather deck, to perform various ship functions, as noted in the following sections.

22.5.2 Anchor Arrangements

All ships are required to carry at least one anchor for anchoring in a seaway. If the ship is classed it will meet the *Equipment* requirements of the classification society. For ocean-going classed ships generally two anchors are required to be carried in an easily releasable arrangement (usually hawse pipes),.and a spare anchor is stowed on the weather deck. The size of the anchor and its chain including the length of chain is determined from the classification society rules (18,19).

There are a number of different anchor types as shown in Figure 22.27. It should be noted that the classification societies allow lighter weight for extra holding power anchors. The anchors are normally stowed in hawse pipes, although some innovative alternative arrangements have been used in large commercial ships.

Figure 22.28 shows how an anchor and chain assembly is made up.

The chain is led from the anchor to the anchor windlass or capstan and then to chain pipes that direct the chain into the chain locker (Figure 22.29). The end of the chain (bitter end) is secured to a double padeye and pin in the chain locker that is designed for the pin to break (shear), should the anchor run away and payout free-fall, thus allowing the

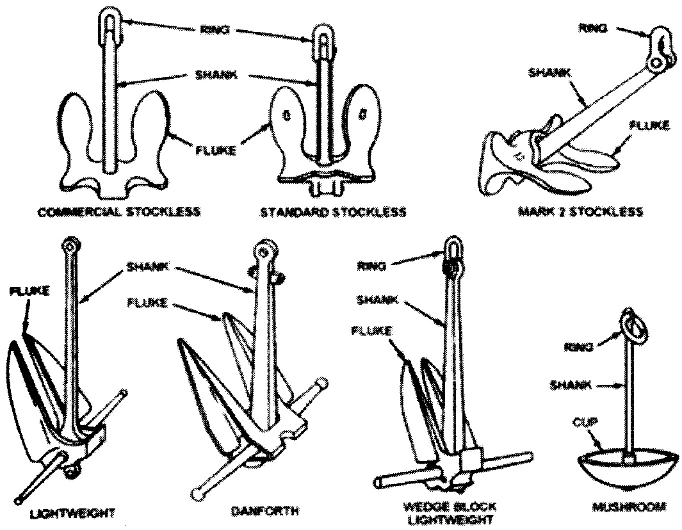


Figure 22.27 Anchor Types

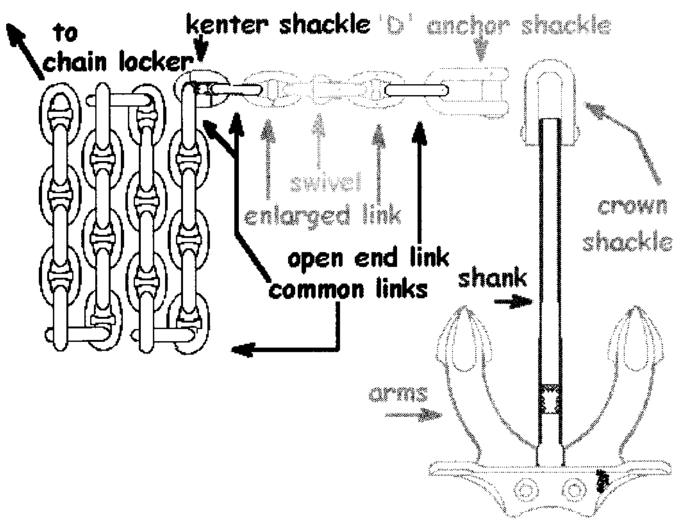


Figure 22.28 Anchor Chain Assemblly

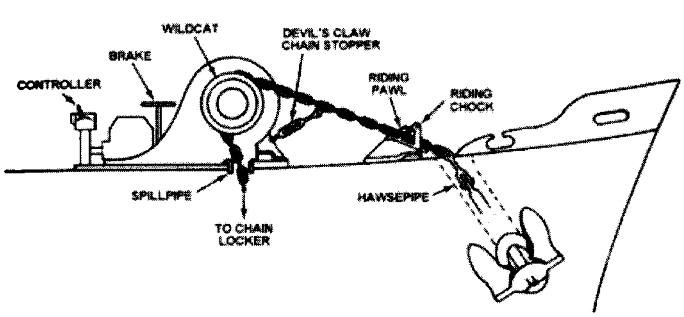


Figure 22.29 Anchor Deck Arrangement

chain end to pass freely over the windlass rather than destroy the surrounding chain lockerlchain connecting structure, which could jam in the windlass causing the windlass to be ripped off its foundation, as has happened in a number of cases.

A perforated thick plate is arrange above the bottom of the chain locker to provide drainage and access space below the chain in the event it is necessary to clean out accumulated mud.

Access into the chain locked from above is usually provided by hand and toe holes in the centerline dividing bulkhead rather than ladders or rungs on which the chain could become snagged.

For small to medium size ships a single double wildcat windlass is normally installed and the chain lockers are located below and adjacent to each other with the centerline bulkhead being non-tight. For larger ships a single windlass arrangement is impractical and separate windlasses are provided for each anchor as shown in Figure 22.30. They will also have two independent and separated chain lockers.

22.5.3 Mooring Arrangements

Mooring arrangement covers the layout and equipment used in mooring a ship. Over time an acceptable layout has been developed and it is based on arranging line handling equipment and fittings to provide 6 to 12, or even more for speciallarge ships, mooring lines on each side of the ship as follows:

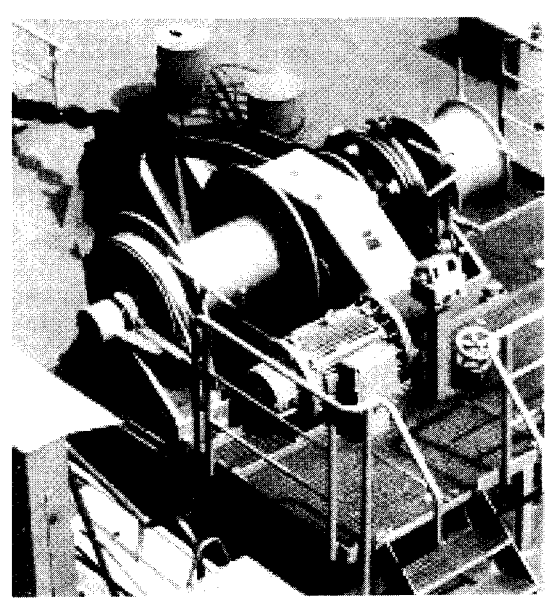


Figure 22.30 Split Anchor Windlasses

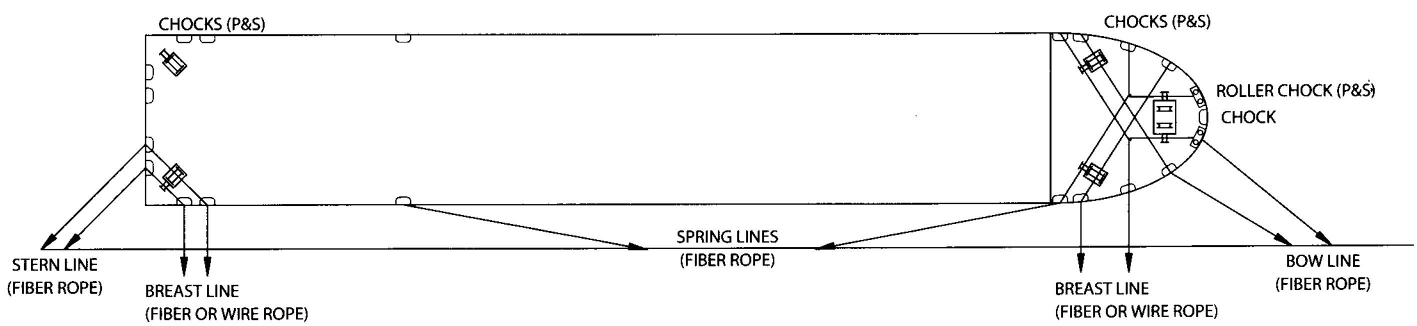


Figure 22.31 Typical Mooring Arrangement

1. bow line,
2. forward breast line,
3. forward spring line,
4. aft spring line,
5. aft breast line, and
6. the stem line.

The lower number is used for normal weather and the higher for heavy weather mooring. To provide 12 lines the above 6 are doubled up.

The many different mooring arrangements for different ship types can be seen from the general arrangements in each of the ship design chapters in Volume II and should be carefully studied to see and understand why they are so arranged. However, a typical mooring arrangement is shown in Figure 22.31 and in more detail for the forward end of a ship in Figure 22.32.

The size of the mooring ropes and wires is determined from the classification society *Equipment Number/Numeral.* However the sizing of the winches must be determined from calculations that take into account all the mooring forces resulting from wind and current. This may be perfo~ed by the ship designer or it may be performed by the winch supplier as part of his service to the shipyard. Guidance on this matter can be obtained from four excellent publications of the old (now defunct) British Ship Research Association (BSRA) (20-23) and summarized in an excellent paper by Ivar Krogstad (24).

In the design of the mooring system two conditions, each considering wind and current, are used to determine the most severe forces acting on a ship as follows:

Condition 1:
- wind speed of 60 knots acting in any direction,
- a current of 5 knots acting transversely from the mooring pier, and
- a current of 2.5 knots acting at an angle of 10° to the ships centerline (only the transverse component of this action is considered).

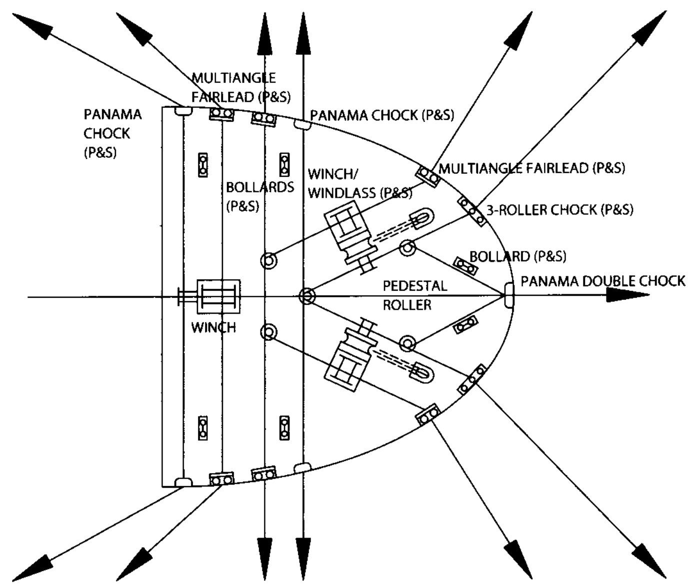


Figure 22.32 Foredeck Mooring Arrangement

Condition 2:
- wind speed of 33 knots acting in any direction, and
- currents same as Condition 1.

When calculating the longitudinal force the first two factors are combined and for the transverse force the first and last factors are combined.

Mooring equipment falls into two broad categories, mainly those featuring constant tension winches which permit constant, automatic adjustment of mooring lines where changes in draft at the loading pier due to tide or discharging of cargo is frequent and significant, and those mooring arrangements in which fiber and/or wire-rope mooring lines are manually adjusted periodically, when necessary, with the aid of capstans or warping heads on the anchor windlass and secured to mooring bitts.

The minimum number of winches is four, all of the same size. The windlass warping heads are an additional moor-

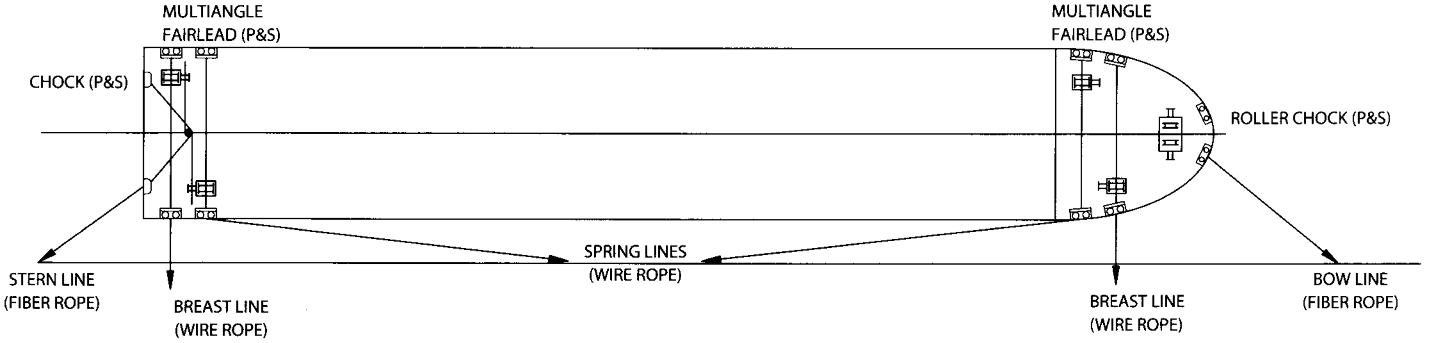


Figure 22.33 Typical Mooring Arrangement with Constant Tensioning Winches

ing aid. For ships larger than 1O 000 tonnes DWT six winches is the minimum. Also, for larger shipss two windlasses are supplied and each can have a rope drum as well as a warping head (Figure 22.30). The bow and stem lines are normally fiber-rope and the breast lines are normally wire rope. Automatic/constant tensioning winches are used to handle only breast and spring lines.

The desire to reduce crew size has resulted in more ships installing constant tension winches. Also, constant tension winches become desirable for larger ships of most types and are essential for tankers, bulk carriers, and containerships which can load and/or discharge their entire cargo in a few hours, thus requiring continual adjustment of mooring lines to compensate for large, rapid changes in draft.

Constant tension winches also enable a dry bulk carrier to be conveniently moved fore and aft to various loading stations along the pier, as is standard practice for Great Lakes ore ships. The ship's position is changed by manually controlling certain winches to payout in one direction while other winches take in line in the opposite direction, as conditions dictate. Once the ship has moved to the temporary new position, the winches are set to resume automatic constant tension operation. Another advantage of constant tension winches is that the lines are stowed on their main drums. Setting the mooring winches to payout and reel in the mooring cables at a pre-set load automatically accommodates changes in ship draft.

Figure 22.33 shows a typical mooring arrangement for a ship equipped with constant tensioning winches, and Figure 22.34 shows a typical winch that can be either normal pull or automatic (constant tensioning) pull.

A special winch for handling fiber rope at high payout and inhaul speed is the traction winch shown in Figure 22.35. Another special winch and its associated equipment is the emergency towing gear that is required by law to be installed on ships, such as tankers that must have escort tugs in attendance when entering specific sounds, bays and harbors (Figure 22.36). The crew on the attending escort tug

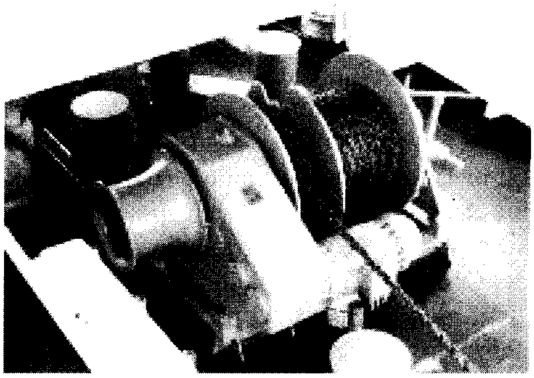


Figure 22.34 Mooring Winch

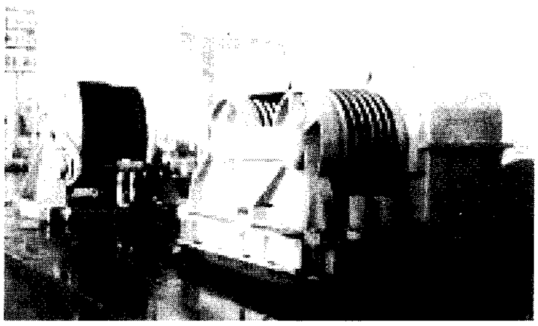


Figure 22.35 Traction Winch

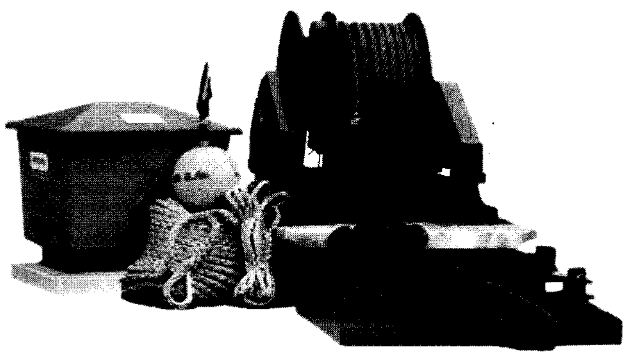


Figure 22.36 Emergency Towing Gear with Special Winch

initiates the use of the emergency towing gear, when the ship advises them they have lost control of the ship or are experiencing other problems.

22.5.3.1 Mooring bitts, cleats, and rings

Mooring bitts are cast steel or fabricated of vertical heavy pipe barrels welded to a dished base plate, which in turn is welded to the deck. Local reinforcement is usually added directly below deck to properly distribute the reactions into the adjacent side and deck-framing members. The size of the bitts installed varies with the diameter and strength of the mooring lines to be used, and is designated by the diameter of the two pipe barrels. Typical welded bitts are shown in Figure 22.37.

Bitts on special ships such as tugs are usually constructed with the barrels extending below the deck in order to carry the large loads such bitts experience in service.

Recessed mooring bitts are sometimes installed in the side shell of large ships with high freeboard between the water line and the weather deck at a convenient height for tug, barge or small craft crews to handle their mooring lines when alongside. They usually consist of a recessed steel casting with a special vertical horn, and are set between frames flush with the shell plating (Figure 22.38).

22.5.3.2 Chocks, fixed and roller

Chocks are installed at the sides of the ship to lead the mooring lines from their fixed point on shore to the hauling end or attachment aboard ship. The latter point may consist of mooring bitts, warping head, or capstan in the case of fiber rope mooring lines or a constant tension winch in the case of wire rope.

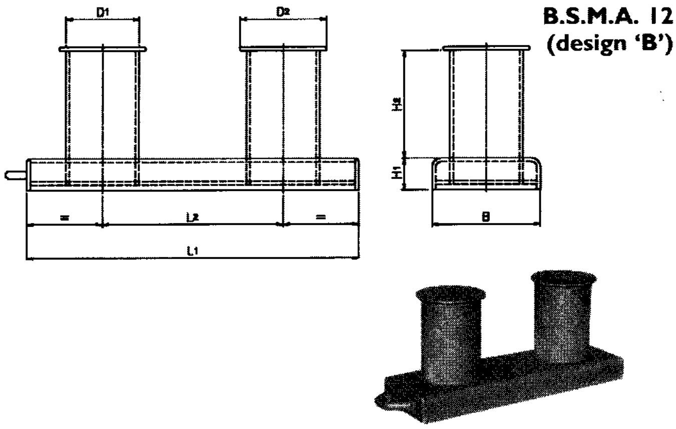
Fixed chocks are used for fiber rope hawsers, which do not require adjustment under load, but roller fairleads are preferable to minimize friction on the mooring lines and/or wh~re the lines are normally frequently hauled in and paid out. Fixed chocks are often called *closed* or *Panama Chocks* because ships passing through the Panama Canal have to be fitted with them (Figure 22.39). This is because the ship is connected to a number of trains that pull the ships through the locks.

Fixed chocks consist of a steel casting or weldments, having an oval-shaped opening with well-rounded edges to reduce chafing action (Figure 22.40).

If the chock is to be mounted on deck, it will have a flat base, which is welded to the deck. If the chock is bulwark mounted its periphery will be oval shaped and will be welded directly to the bulwark plating with local stiffening between brackets.

Roller chock frames are steel castings or elements in which rollers are mounted. Roller chocks used in conjunction with fiber rope generally have only vertical cast concave-shaped rollers at the end of the opening whereas chocks intended for constant tension winches with wire lines are fitted with four pipe rollers (two vertical, two horizontal) so that a roller is brought into play for any direction of line pull to the pier (Figure 22.41).

Supplementing the fixed or roller chocks as discussed



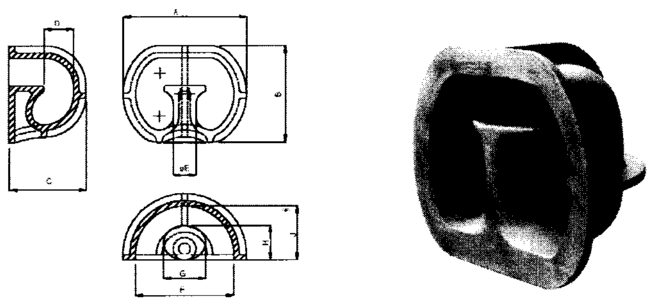
Type	f		TUBE		PLATE		l_1	l_2	h_1	h_2	b	d_2	Wt. Kg.
	M	T	d_1	s	d_1	s							
125	4.06	12	140	10	125	10	560	320	200	75	200	150	40
160	5.85	12	168	10	160	10	720	400	250	90	250	200	66
200	7.96	17	219	10	200	10	900	500	300	100	300	250	97
250	13.2	30	273	10	250	10	1130	630	380	125	380	300	145
315	19.7	50	32.4	12.5	312	12.5	1430	800	480	150	480	400	309
400	33.5	100	406	20	400	20	1800	1000	600	175	600	480	735
500	55.4	130	508	20	500	20	2250	1250	750	200	750	600	1148
630	82.8	160	610	20	630	20	2830	1570	940	225	940	730	1673

Maximum permissible load in bollard = f tonnes
When mooring = M tonnes
When towing = T tonnes

(1) The bollard can be loaded with two mooring ropes each with a breaking strength not exceeding the values in the table.

(2) The bollard can be loaded with one towing rope laid in single sling over one of the bitts and with a breaking strength not exceeding the values in the table.

Figure 22.37 Mooring Bitts



Nominal Size of Bitts (Tonne)	Weight Kilos	A mm	B mm	C mm	D mm	ØE mm	F mm	G mm	H mm	J mm
20	105	440	350	250	105	81	360	150	125	230
50	285	850	660	445	115	165	675	355	240	362

Figure 22.38 Recessed Mooring Bitts

previously, rollers are installed on pedestals where required for leading lines to a warping head or capstan from the mooring fittings at the ship's sides (Figure 22.42).

22.5.3.3 Modern automated mooring systems

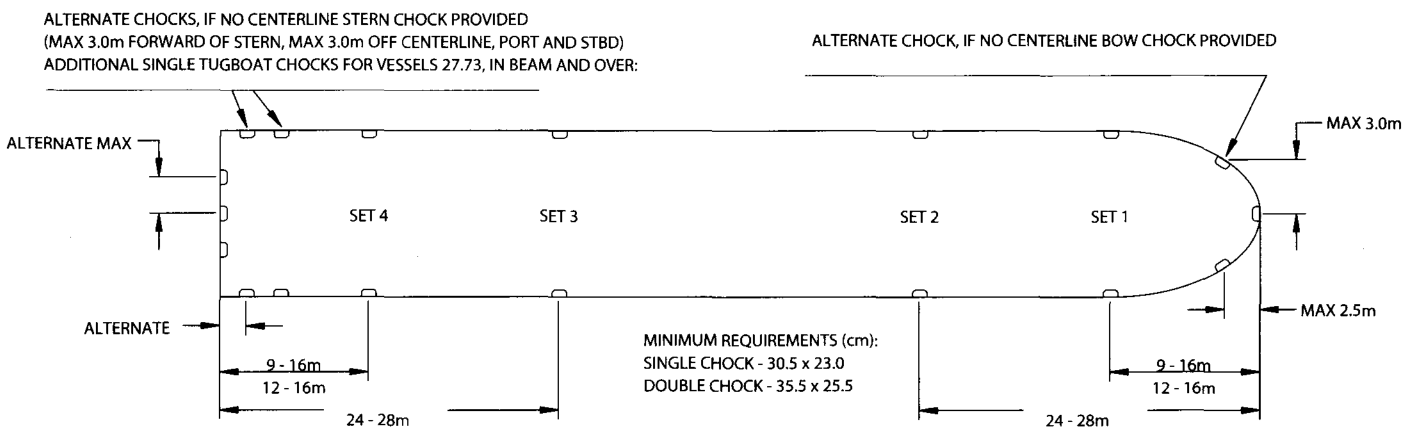
There are a number of companies that have developed automated mooring systems. One system uses vacuum pads on a framework on the quay, which extends out and secures (by vacuum) to the ship's side. It then slowly brings the ship into the final moored position. Another company uses giant magnets instead of vacuum. The obvious drive to develop and use such systems is:

- elimination of shore mooring gangs,
- elimination of ship line crew,
- one operator to moor the ship,
- minutes instead of hours to moor a ship, and
- the eventual elimination of the need for mooring winches onboard ships.

22.5.4 Bulwarks, Rails, and Stanchions

Bulwarks are fitted on the weather deck as a protection from seas for personnel and deck cargo. They are of heavier construction than those on superstructure decks, owing to the greater possibility of damage from seas as well as to provide sufficient strength for attachment of rigging fittings, lashing deck cargo, etc. Adequate freeing ports must be provided for drainage in accordance with load line regulations.

Bulwarks are usually constructed of steel plate not less than 6 mm thick supported by flanged plate brackets spaced 1.5 to 1.8 m apart. On vessels subject to load line regula-



VESSEL SIZE	CHOCKS REQUIRED
VESSELS UNDER 60.96m O.L. AND LESS THAN 15.24m BEAM (VESSELS OVER 38.10m O.L. AND 15.24m BEAM OR OVER REQUIRE SET 1 AND SET 4 ALSO)	BOW CENTERLINE (DOUBLE) STERN CENTERLINE (DOUBLE) TWO SINGLE (ALTERNATE IF NO CENTERLINE PROVIDED)
VESSELS FROM 60.96m TO 121.52m O.L. AND LESS THAN 22.86m BEAM	IN ADDITION TO BOW AND STERN ABOVE SET 1 (SINGLE 9 TO 16m ABAFT OF STEM) SET 4 (SINGLE 9 TO 16m FORWARD OF STERN)
VESSELS OVER 121.92m TO 173.74m O.L. AND LESS THAN 22.95m BEAM	IN ADDITION TO BOW AND STERN ABOVE SET 1 (DOUBLE 12 TO 16m ABAFT OF STEM) SET 2 (SINGLE 24 TO 28m ABAFT OF STEM) SET 4 (SINGLE 12 TO 16m FORWATRD OF STERN)
VESSELS OVER 173.74m O.L. OR 22.86m BEAM OR OVER	BOW CENTERLINE (DOUBLE) STERN CENTERLINE (DOUBLE) TWO DOUBLE (ALTERNATE IF NO CENTERLINE PROVIDED) SET 1 (DOUBLE 12 TO 16m ABAFT OF STEM) SET 2 (SINGLE 24 TO 28m ABAFT OF STEM) SET 3 (SINGLE 24 TO 28m FORWARD OF STERN) SET 4 (DOUBLE 12 TO 16m FORWARD OF STERN)

NOTE— VESSELS OF 27.73m BEAM OR MORE WITHOUT A CENTERLINE STERN DOUBLE CHOCK WILL REQUIRE TWO DOUBLE ALTERNATE CHOCKS AND TWO ADDITIONAL SINGLE TUGBOAT CHOCKS

Figure 22.39 Panama Canal Mooring Fitting Requirements tions, the upper edge of the bulwark must be at least 1 m above deck and suitably stiffened with a flat bar, angle, bulb angle, or channel. (An exception to this is 0.76 m for towboats.) Where extra strength is needed, such as on the forecastle, a longitudinal intercostal member is fitted at mid-height. On passenger decks a teak or a polished non-corrosive metal cap rail, is sometimes fitted directly over the steel top member, or mounted on short pipe stanchions 1500 to 2300 mm above the steel to form a *monkey rail.*

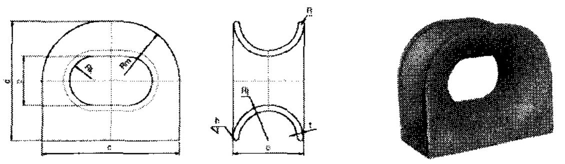
In free or floating bulwarks, the plating is not attached directly to the main structure (side shell) of the ship. The advantage of this arrangement is that the bulwarks arenot welded to the sheer strake and thus do not act as part of the ship girder, and can therefore be of much lighter construction. This construction also prevents cracks, which may originate in the light bulwark plating, from progressing down into the deck stringer and sheer strake. The 1500 mm of space between bulwark and sheer strake also provides a continuous freeing space in place of the customary freeing ports.

Bridge front bulwarks are usually higher (1350 mm) and fitted with a venturi type wind shield, which deflects the wind upward, thus minimizing the airflow striking personnel on the open bridge.

Breakwaters are of similar construction to weather deck bulwarks; however, they are of considerably heavier construction, to withstand the direct impact of seas and are of plow form to deflect the seas laterally. The height of the breakwater is made greater than that of the hatches or equipment it protects. Container ships have special high breakwater structures to protect the deck-stowed containers.

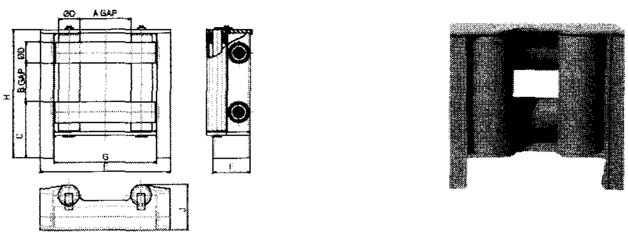
Open rails are fitted along the edges of decks unless bulwarks are fitted. The regulatory body rules specify three-

Type	Kn	B1	B2	E	F	H1	H2	H3	L2	R1	R2	S1	S2	W1	W2	Kg
A5	50	480	340	240	24	300	80	38	550	150	90	16	8	250	180	74
A8	80	585	415	292.5	27	260	90	45	680	180	112.5	18	9	320	225	120
A12	125	710	500	355	30	440	110	55	840	220	135	20	10	400	270	185
A20	200	840	595	420	33	520	130	35	1020	260	160	22	11	500	320	285
A32	320	1100	800	550	-	700	150	80	1300	350	200	35	20	600	400	795



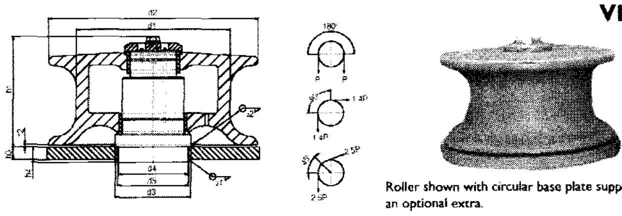
Std	Size	a	b	c	d	e	Rj	Rk	Rm	R	t	h	Wt Kgs
VIS 3 Swedish Std	300 x 200	300	200	530	430	230	115	100	215	12.5	25	8	85
VIS 3 Swedish Std	400 x 250	400	250	760	610	360	180	125	305	12.5	25	8	185
DVS 47005 Danish Std	300 x 250	330	250	660	610	360	180	125	305	10	20	6	117
DVS 47005 Danish Std	400 x 250	400	250	760	610	360	180	125	305	12.5	28	8	185
NS 2590 Norsk Std	300 250	300	250	660	610	360	180	125	305	10	20	[illegible]	117

Figure 22.40 Closed/Panama Canal Chocks



Type	Part No.	S.W.L. (tonnes)	ø Wire rope	A	B	C	D	E	F	G	H	J
114	A2-605	5	-10	254	152	309	114	686	203	534	645	248
140	A2-608	8	-16	254	152	335	140	756	254	578	697	300
168	A2-610	12	-20	254	152	363	168	812	305	634	753	356
194	A1-612	20	-28	324	200	389	194	966	381	762	853	408
273	A1-614	24	-32	324	200	543	273	1124	432	920	1111	566

Figure 22.41 Multiage Roller Fairleads



Roller shown with circular base plate supplied as an optional extra.

Size	d_1	d_2	d_3	d_4	d_5	h_1	h_2	h_3	h_4	s_1	s_2	P tonnes
150	150	240	105	85	90	158	5	25	40	8	6	15.8
200	200	310	130	110	115	190	5	25	40	8	6	19.8
250	250	380	150	130	135	245	6	25	40	8	8	28.5
300	300	440	170	150	155	270	7	35	50	8	8	33.6
350	350	500	190	170	175	294	7	35	50	10	10	44.8
400	400	560	200	180	185	332	7	35	50	12	12	58.0
450	450	630	225	205	210	341	7	35	50	12	12	64.2
500	500	680	245	225	230	358	7	40	50	15	15	84.3

P = breaking load in tonnes on the line which is to be used with the roller fairlead.

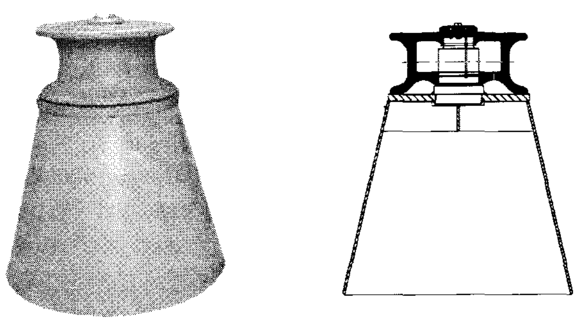


Figure 22.42 Rollers and Pedestal

course rails, of definite height, at the shell and prescribe the rail spacing. Two-course evenly spaced rails are prescribed at other than exposed peripheries.

Open rails generally are constructed of steel pipe attached to stanchions spaced approximately 1.5 m apart. The upper rail is located 1.07 m above the deck and is heavier than the intermediate rails. The stanchions can be flat bars, structural tees, etc. On decks used by passengers, a teak or polished non-corrosive metal cap rail is frequently fitted. When used on the weather deck of a cargo ship, they are usually made portable in way of the cargo hatches to facilitate loading, and to minimize damage. The portable section of an open pipe railing is made up in sections about 1.8 to 3 m in length, convenient for handling manually. The stanchions are set into deck sockets and secured with brass toggle pins, attached with keeper chains. Pipe braces bolted to deck lugs laterally secure the ends of a portable section. Chain rails constitute a convenient type of portable railing, commonly used at a ship's side abreast of cargo hatches, around deck openings, etc. The stanchions are set into deck sockets and galvanized chains are rove through eyes in the stanchions. One end of a length of chain is shackled to a lug while the other end is set up with a turnbuckle secured to the deck. The chain size is usually 8 or 9 mm, depending upon the nature of the duty.

Guardrails are fitted around openings in decks, at sideports, escape trunks, etc., and may be made of either pipe or chain as required. Portable guardrails are also fitted around exposed moving parts of deck machinery for protection of personnel. Grab rails or storm rails are fitted around the outside of deckhouses as well as along one side of interior passageways, service spaces, etc., to provide a safe hand grip for personnel walking about the ship in heavy weather. Where passageways are 1.8 m wide 0J more, a handrail must be fitted on each side. They are usu~ally located about 0.9 m above the deck and secured with bulkhead-mounted brackets or sockets spaced 1.2 to 1.5 m apart. The rails are set away from the bulkhead not less than 50 mm to afford a convenient handgrip. Galvanized-steel pipe is commonly used for grab rails on weather decks and in crew quarters. In the wheelhouse and passenger areas, the grab rails are made of hardwood, aluminum or stainless steel.

Provision is usually made (though less frequently today) for fitting awnings of canvas, nylon, Dacron, or other rigid noncombustible material over certain deck areas for the comfort of the ship's personnel. Common locations are the poop deck and the weather deck aft of the deckhouse.

If fitted, most commercial ship operators prefer permanent, rigid awnings made of a variety of materials such as corrugated aluminum; translucent corrugated glass reinforced plastic (GRP), flat GRP panels bolted to a suitable framework of galvanized structural sections.

A *rain shelter* is required by the Panama Canal Authority, on the extreme outboard location of the open bridge, for the Canal Pilot. Details can be found in the Canal regulations.

22.5.5 ladders and Stairs

Ladders are installed to provide suitable access or means of escape as required by regulatory body regulations.

22.5.5.1 Fixed vertical ladders

Vertical ladders are fitted for access to all cargo holds, boson's stores, tanks, etc., where inclined ladders or horizontal access is not possible. In general, two ladders are provided to each space where practicable. Vertical ladders require climber safety devices and a platform every 6 m. On some ships, additional hold ladders are fitted at the transverse bulkheads with a deck hatch or hinged manhole overhead. In containerships the inclined ladders are located at the bulkheads or the shell.

Access to boson's stores, and in some instances steering-gear compartments, is provided through a hinged deck hatch with ladder below. Access to non-cargo tanks is made through a bolted manhole.

A common method of constructing vertical ladders is using two 150 x 100 x 10 mm angle stringers 280 mm apart with 16 mm square rungs on 300 mm centers welded to the stringers. The rungs can be placed with either the flat or the corner up; the latter is generally considered to be safer since it affords a more certain footing, particularly in deep tanks where the ladders are frequently oily. Vertical ladders usually are made up in sectiens and bolted to lugs or clips, which are welded to the ship's structure. In some instances it is possible to omit the stringers and merely weld the rungs directly to bulkhead stiffeners or the shell frames. In shallow tanks, such as double bottoms, the rungs generally are formed into a stirrup with the ends welded to the bulkhead or floor plate.

22.5.5.2 Spar ladders

Ladders must be installed on masts, kingposts, stacks, etc., to provide access for servicing of radar, antennae, lights, rigging fittings, blocks and lines. On large masts the ladders are usually made up of76 x 10 mm flat-bar stringers spaced 300 mm apart with 16 mm square rungs on 300 mm centers, and are bolted to lugs welded to the mast, similar to a hold ladder. Spars less than about 400 mm in diameter, generally are fitted with stirrups shaped in such fashion that a person's foot will not slide off sideways. In way of rigging fittings, etc., where work is to be performed aloft, climber safety devices are installed. Care must be taken to arrange ladders in the safest possible position.

Spar ladders are provided for interior inspection and maintenance of large-diameter masts and kingposts. Usually this type of ladder consists of rungs or stirrups welded to the inner wall on one side of the spar. Access is obtained through a manhole and bolted cover, located near the point at which the bending stress is minimum.

22.5.5.3 Inclined ladders

Inclined ladders are provided on all weather decks for access from one deck level to another. The regulatory body regulates the degree of incline. This type of ladder is also found in stores spaces. Generally, an inclined ladder resembles a stair, the principal differences being steeper pitch and the omission of risers. The ladder is made up as a unit, complete with stringers, treads, and handrails. The assembly is then bolted or welded at the top and bottom of the stringers to the decks. The stringers generally are light channels spaced 760 mm apart. Treads are steel with nonslip covering and are welded to the stringers. A nonslip deck pad is located at the top and bottom of all inclined ladders. Rails usually are made up of 32 mm pipe. For safety, weather deck inclined ladders are located to avoid tripping hazards on deck, as well as cargo gear and other deck machinery. The cargo tanks in tankers are usually fitted with a short (about 3 m) vertical ladder to a platform below the deck and from there with high angle inclined ladders and intermediate platforms.

22.5.5.4 Accommodation ladders

Accommodation ladders, by which the ship is boarded from a boat or pier, are required to reach from the weather feck level to the light operating draft line at an angle of approximately 45° to the horizontal. The length of the ladder is adjustable to variations between light- and full-load draft by modifying its angle, by telescopic action, or by extending an adjustable lower section.

The side stringers are made of lightweight metal (usually aluminum) channel sections, or of wood, and are usually designed for an assumed load of 136 kg per tread. The treads are shod with nonskid material or strips, and are either positioned to be horizontal when the ladder is in working position of 45 degrees or feathering treads are arranged to pivot automatically to the horizontal for any working angle. Some ladders have curved-upwards treads that are suitable at all operating angles.

The upper end of the ladder pivots from a portable platform grating attached to the ship's side at deck level. A similar platform is fitted at the lower end to facilitate boarding from small craft or the pier. The ladder and platforms are equipped either with foldable guardrails with sockets to take portable guardrail stanchions. The wire rope guardrails,are rigged through eyes on the stanchions. Canvas, Dacron, or nylon weather cloths along the rails are fitted and fastened with braided nylon lacing cord.

When in its working position, the lower portion of the ladder is supported by wire-rope slings attached to an adjustable tackle or mechanical hoist system. The upper end of the block and tackle is shackled to a davit head or fixed-point overhead. The lower ends of the slings are spread apart by a spacing bar or bridle to provide suitable headroom.

The accommodation ladder is stowed by hauling it up to a horizontal position at deck level with the supporting tackle. It is then lifted inboard by means of davits and tackles, and usually is stowed on its side on deck adjacent to a recessed raillbulwark to be flush with the ship's side.

Normally, the port and starboard accommodation ladders are located on the upper deck. Its working position is carefully selected to keep it well clear of overboard discharges and cargo loading sideports and have its upper terminus adjacent to a ship's office, watch station or quarterdeck for naval ships.

22.5,5.5 Stores and service handling gear

Davits, cranes, and tackle are commonly used to handle bosun's stores and on smaller ships, to hoist or lower single items or packages through stores hatches. The out-reach of a davit is relatively short, being intended to swing loads over a hatch opening from a position on deck alongside the hatch. Cranes, on the other hand, generally have sufficient outreach to hoist loads from the pier to points on deck near a stores hatch, or over the hatch opening.

Davits are of simple construction consisting of a rotating bracket arm pivoted from a deckhouse bulkhead or other conveniently located structure. A block and tackle is suspended from an eye at the end of the arm. The shipbuilder often fabricates davits whereas cranes tend to be more elaborate, frequently having extendible, telescoping booms with hydraulic drive. Cranes usually are stepped on the weather deck about half way out from the centerline to the side of the ship port and starboard, to minimize boom length.

Elevators are in wide use on ships built in recent years due to the trend towards large ships with many deck levels, which make stair climbing a tiring, time-consuming chore. Shipboard elevators ride on guide rails in an *A Class* steel trunk and are of similar size and operation to those used in small apartment houses. Ship elevators are frequently used to move stores as well as personnel.

Dumb-waiters are extensively used to move food from a galley or pantry on one deck level to dining or mess rooms located on other deck levels. The dumb-waiter is also used to move cartons of food products from the stores loading deck to the galley area. Controls are located on each deck served by the dumb-waiter.

Conveyors are used to load food stores and for package cargo handling. Horizontal-belt conveyors rigged through sideports provide a rapid means of loading packaged items, such as cartons of canned goods or crates of fruit, and are fitted in the upper tweendecks. Vertical conveyors move similar unitized cargoes through hatch openings from one deck level to another. Horizontal and vertical conveyors are thus commonly used in combination on fruit ships and other types of unitized package cargo carriers. Conveyors are also used for food stores handling on large passenger or naval ships on which striking down stores for a large number of people must be accomplished in a relatively short time.

22.5.5.6 Deck stowages

On break-bulk general cargo ships lashing pad eyes are fitted on weather decks abreast of the hatches. The eyes are spaced 1.2 to 1.5 m apart near the hatch side and at corresponding points near the sides of the ship so that lashing cables or chains can be rigged over the deck cargo. The pad eyes are made of plate, about 19 mm thick, with a hole to fit the pin of a 25 mm shackle, or formed of V-shaped staples of 25 mm diameter rod with both ends welded to the deck. Pad eyes preferably should be attached directly above a deck beam, bulkhead, or other rigid structure; otherwise local reinforcement must be provided in way of the pad eye.

The container stowage on containerships is a highly developed system of locking fittings and lashings (see Chapter 36 - Container Ships).

Pure Car Carriers and RO/RO ships have special deck fittings to which vehicle lashings can be secured (see Charter 34 - Car Carriers and Chapter 35 - RO/RO Ships)

22.5.5.7 Spare parts stowage

In general, miscellaneous spare parts are labeled and stowed out of the weather at convenient locations. For example, machinery spares, valves, pipe, etc., are stowed in racks in the engineers' stores room. Spare armatures, brushes, etc., are stowed on shelves in the electrical stores room. Steering-gear spare parts are stowed in chocks or on shelves in the steering-gear room. Other heavy spare parts are similarly stowed in chocks in convenient locations. Parts vulnerable to damage by salt air are suitably protected with grease, sealed packaging, or other appropriate means.

22.5.5.8 Rigging fittings

Today very few ships are fitted with derrick and cargo booms to handle the cargo. If onboard cargo handling is provided it is usually cranes. Some heavy lift ships still have unique design heavy boom with special derricks (see Chapters in Volume II for specific applications of cargo handling gear), but even they are being replaced by cranes.

Miscellaneous rigging fittings are still used throughout the ship for cargo securing and moving stores and spares within the engine room and accommodation. Pad eyes are also provided throughout the ship (inside and outside) to assist when the ship is being repaired or overhauled, such as those in the stem region to handle the ship's propeller.

22.6 PILOT BOARDING

22.6.1 General

Pilot boarding, while not an emergency situation, involves similar personnel risks to those dealt with in lifesaving system design. It is included here since the design considerations are similar. Provision for boarding at sea of persons other than pilots should be given the same consideration.

Pilot boarding is a frequently repeated occurrence during the life of a ship, often involving considerable risk to human life. Since it is routine, it is often neglected in basic ship design and thus can pose a number of problems to owners and operators, not to mention pilots.

22.6.2 Design Features

The Safety of Life at Sea (SaLAS) Convention and government marine safety regulations specify the design details for pilot ladders and powered pilot hoists and their arrangements. The basic ship design principle is to provide a straight, clear side to permit the ladder to lie flat against the vessel from the bottom of the ladder to the point of access with a straightforward direct transfer over the gunwale. Provision for boarding at either side should be made.

Pilots should not climb ladders for more than 9 m or less than 1.5 m. For greater distances, an accommodation ladder leading aft or other means should be provided. Sideports should be of adequate size and height to facilitate safe entry and any closure should be designed to not interfere with operation of pilot vessel including its antenna. Provision for over-the-side lighting should be made as well as for the deck landing area. Design features which complicate safe boarding include decks projecting beyond the ship side, non-vertical sides, rounded bulwarks, boarding hatches, outward opening doors that get in the way of the pilot vessel, boarding hatches too low to permit a quick climb up the ladder to safely clear the pilot vessel, rubbing bands, overboard discharges, and failure to provide clear access to the deck with adequate handholds. A recent development gaining

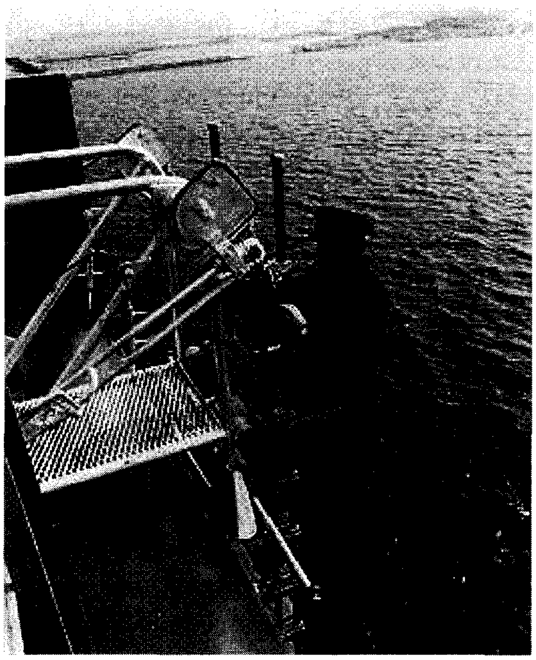


Figure 22.43 Pilot Hoist Ladder

popular acceptance is a pilot's boarding hoist raised by a power winch (Figure 22.43).

Provision is made for this portable unit, both port and starboard, on permanent platform locations. The installation is particularly advantageous on larger ships.

22.7 HOLD SPARRING, CEILING, AND DUNNAGE

22.7.1 General

The items covered in this section serve primarily to resj"ain and protect the various types of cargo carried in break-bulk cargo ships. It should be noted that break bulk cargo ships have become a rarity today in international oceangoing service, being replaced by the multipurpose cargo ships (see Chapter 27 - Multipurpose Cargo Ships). However, there are some still operating in short haul intercoastal trade, but even here they are being replaced by container ships.

Ceiling and sparring are required in cargo holds and storerooms to protect cargo and stores from damage due to condensation, contamination from previous cargo, or damage caused by abrasive action in way of stiffeners, brackets, and beam knees; and to insure proper ventilation of the space. As a general rule, the cargo is stowed so as not to come in contact with steel, except for various types of dry bulk cargoes such as grain, coal, and ore plus some chemicals such as sulfur and phosphate.

Certain types of vessels, such as refrigerated ships, have all the necessary fittings for proper stowage installed during construction (see Chapter 28 - Reefer Ships).

In a ship designed for general cargo, the fittings necessary for cargo protection vary for each type of cargo to such an extent that only a limited installation is made during construction. During operation, it becomes necessary to provide supplementary protection in the form of dunnage, arranged to suit the type of cargo carried on each voyage.

Figure 22.44 shows a section through a general cargo ship hold and typical locations of sparring. The fitting of sparring in all ships of this type and of ceiling in single bottom ships, and under hatch openings in ships with double bottoms, in cargo holds, is a requirement of the classification societies.

22.7.2 Sparring or Battens

The term *sparring* includes wood or metal protection of all vertical surfaces in way of shell frames in cargo holds, in way of all sides in storerooms used for bulk stowage, in way of fuel oil, lube oil, peak tanks, settling tanks, and distilled-water tanks where exposed in cargo holds, cargo tweendecks, or forming the boundary of storerooms. Storerooms that adjoin heated tank bulkheads should be avoided to eliminate need to provide thermal insulation. Sparring is fitted in refrigerated stores, even though completely insulated and lined, to allow for adequate ventilation.

Cargo batten is the term used for units of sparring on shell frames in cargo spaces. These battens are about 150 by 50 mm usually of Douglas fir, fitted horizontally with about a 230 mm space between them. Battens are beveled on all edges to prevent tearing or chafing of bagged or other types of cargo, and are secured to frames by means of clips as shown in Figure 22.44. The large number of clips required has led to the development of special types, which can be attached quickly to frames by spot-welding. The life of cargo battens is relatively short because of rough handling and damage during loading and unloading, and, because they are readily removable, they are often misused by stevedores for dunnage. For this reason some operators insist on bolting them.

At the ends of a general cargo ship with large hatches and fine form, the hold battens are very near the hatch-landing area and are readily smashed by swinging cargo or dislodged in retrieving the cargo hook. A vertical type of cargo batten, also shown in Figure 22.45, has been developed which is unlikely to be caught by a cargo hook and resists a blow from cargo due to its better construction.

The additional cost is offset in part due to the gain in cargo cubic because this type can be recessed in between the side frames and thus will only extend 10 mm, whereas the horizontal type extends 50 mm beyond the frame. On a large general cargo ship, this may amount to as much as 140 m^3 of bale cubic.

Some operators prefer this type for an entire ship, while others have compromised by fitting the conventional horizontal type in all spaces except in end lower holds.

In baggage rooms, all bulk storerooms and in refrigerated stores, vertical sparring is fitted on all walls. Usual practice is to use 50 x 50 mm wood spacers between 200 mm, except that in refrigerated areas the width is increased to 76 mm or more and the spacing is increased to about 305 mm to suit the ventilation requirements. The sparring is fitted around all structural obstructions and over cooling coils and other fittings. When access to these fittings is required, the protective sparring is made portable.

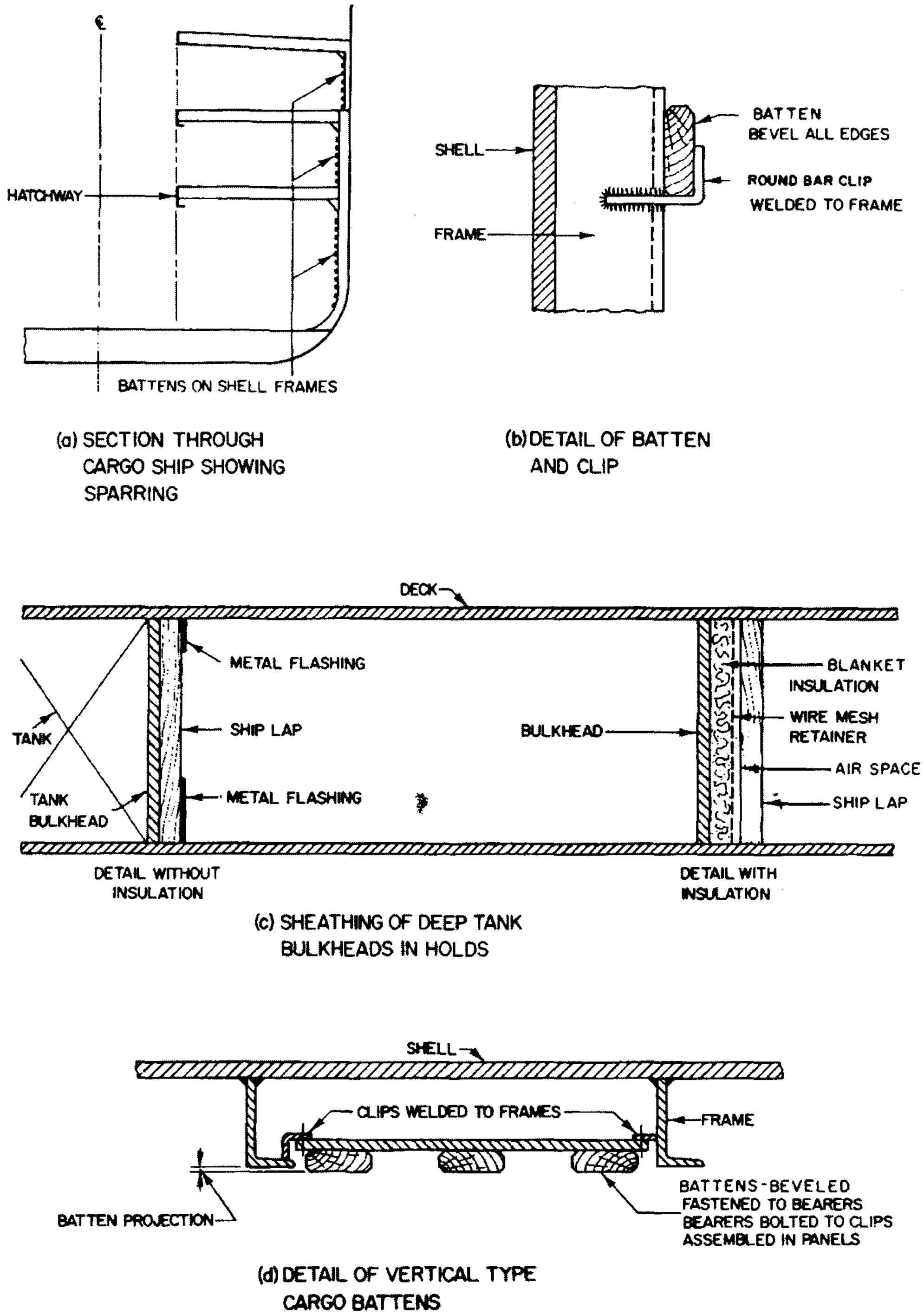


Figure 22.44 Sparring

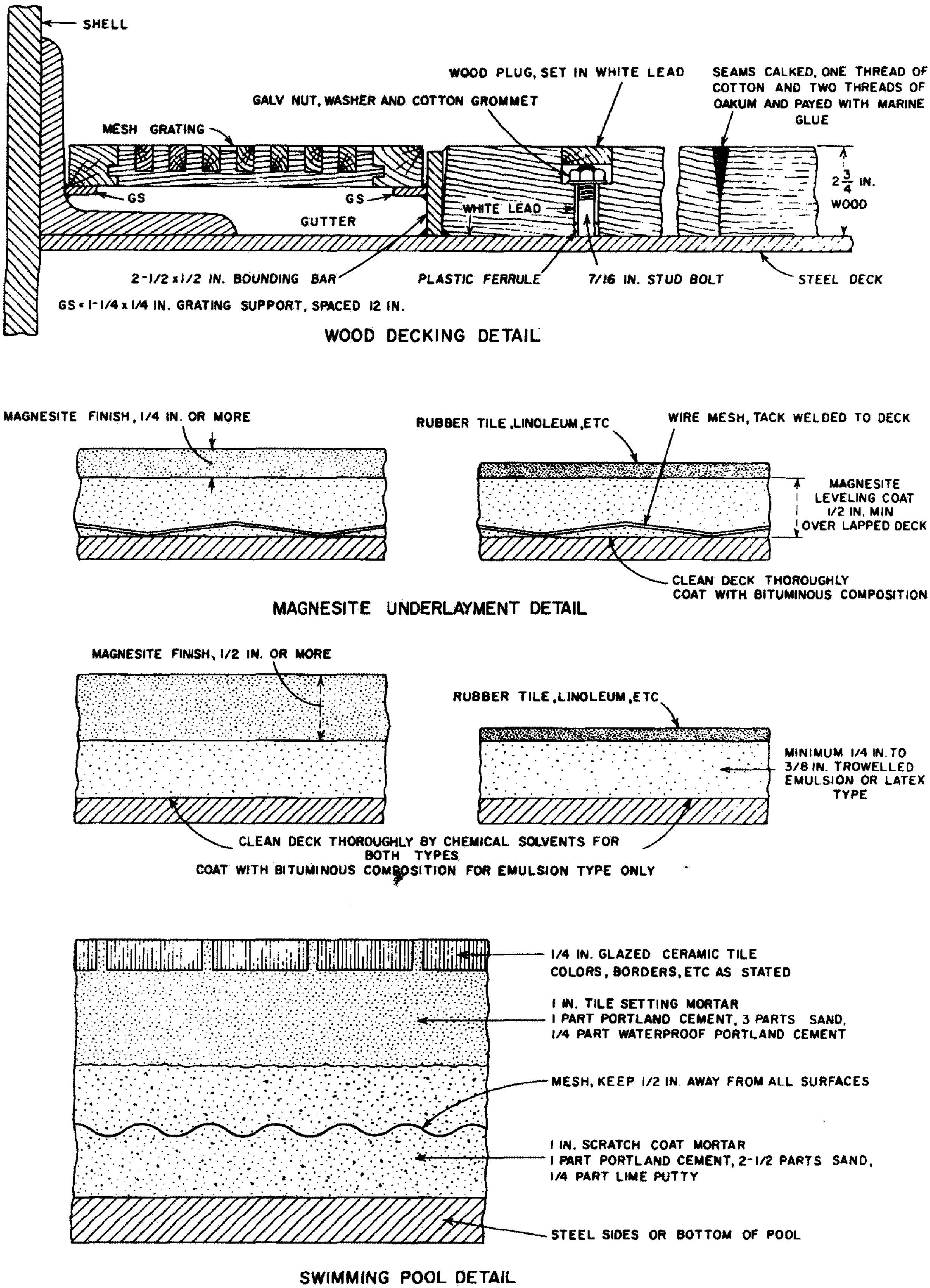


Figure 22.45 Typical Deck Covering Details

22.7.3 Ceiling

To protect the tank top in holds from damage by landing cargo and other cargo handling equipment, such as forklift trucks, ceiling is often fitted on top of the tank top in way of the hatches. It is traditionally wood, but special compositions have also been used.

Dry bulk carriers especially designed for bulk cargoes such as coal and ore do not require sparring and ceiling for protection of cargo. The classification society rules permit elimination of ceilings provided the thickness of inner bottom plating is suitably increased under the hatch openings.

2.7.4 Dunnage and Cribbing

Cargo protection in general cargo ships is usually provided for each loading by the stevedoring concern and consists of wood planks, plywood sheets, temporary bracing, special shoring for deck cargoes, temporary wood bulkheads, shifting boards, etc. In recent years, special patented systems have been developed to eliminate the excessive use of *dunnage* and wood sheathing which is very costly and causes some loss in cargo dead weight and cubic. Such systems consist of wire rope netting with quick-acting lashings on deck and deckhead. The fittings are closely spaced so that practically any type or combination of cargoes may be segregated and permit rapid partial filling and discharge of holds. Plastic inflatable dunnage is occasionally used as well.

There are numerous regulations governing the stowage of cargoes consisting of alcoholic liquors, coal and coke, cotton, grain, explosives, and other flammable or dangerous cargoes. SOLAS 1974 has regulations for the carriage of grain and dangerous goods. The U.S. National Cargo Bureau also issues rules for stowage of grain and cotton cargoes to satisfy insurance underwriters. This discussion will be limited to those fittings usually provided by the s~p-builder for a general cargo ship during construction.

22.7.5 Bulkhead Sheathing

Transverse bulkheads in holds are not usually sparred on the smooth side unless they form boundaries of tanks, in which case they may be insulated and completely sheathed with metal sheathing and sparring. Fuel oil, settling, lube oil, and distilled water tanks which contain heated liquids are sometimes provided with 50 mm of blanket-type insulation, sheet metal lagged under the 50 mm ship-lap covering. Heated tanks should be kept within the machinery space without being adjacent to cargo hold or manned service spaces. Although this may not appear necessary on certain routes, the installation is recommended on dry cargo ships designed for unlimited service and subject to extreme variations in temperatures. Spoilage of cargo due to condensation in holds is of primary consideration since, according to underwriters, sweat damage ruins more cargo each year than any other ocean-shipping hazard.

On some ships, deep tanks also are fitted for carriage of dry cargo. Since these tanks are fitted with heating coils, on bottom and sides it is necessary to provide ceiling and sparring over the coils. To avoid repeated dismantling when changing from dry to liquid cargo, the sparring and ceiling are made of steel and further isolation of dry cargo from the steel is made with dunnage.

22.7.6 Gratings

Wood gratings may be installed in boson's stores, dry stores, refrigerated spaces, and on certain portions of the navigating deck, to provide a dry walking or working surface, although today other materials with better maintenance qualities are used. Those in stores or refrigerated spaces usually are aluminum gratings. More durable molded GRP gratings are now more frequently used in place of wood, based upon specific location and other fire protection considerations.

Metal gratings consisting of galvanized expanded metal, perforated sheets, or aluminum subway-type construction are often used in place of wood gratings and frequently are used in preference to wood in refrigerated cargo spaces where loads are carried on hand trucks or forklift trucks.

Metal gratings are used on tanker walkways and access platforms on the weather deck.

Machinery space gratings in engine rooms are made up of portable sections from steel diamond (non-slip) plate. Gratings are supported by an auxiliary framework, built up of angles and/or rectangular tubing.

Note that galvanized steel and aluminum oxides are carcinogens and should not be used for gratings in areas of food stowage and preparation.

22.8 DECK COVERING

22.8.1 General

The decks of living and working spaces .of merchant ships, with the exception of machinery spaces, are covered by suitable material for comfort, safety, appearance, and in some areas, fire resistance. The coverings usually have some insulating value, provide some sound deadening, and where required include a measure of fire protection. In locations over cargo spaces, the fire protection requirements are met by an approved thickness of noncombustible deck covering material. The details of deck covering for fire protection are dealt with in more detail in Chapter 16 - Safety. Classification society rules permit composition deck covering to be laid over steel not exposed to weather, provided the composition is not corrosive to steel.

The requirements for safety, protection of steel, appearance, minimizing topside weights, plus the ability to provide long-wearing service characteristics for a wide variety of conditions, have made it necessary to develop exacting specifications for deck coverings. Standard government specifications are available for both commercial and naval deck coverings and are invoked by the designer in the ship's construction specification. The leading marine decking manufacturers supply various products under their trade names but each product complies with the standard specification and, in addition, is tested and approved by the regulatory society before being used on ships certified by them. Certain coverings also must be approved by the classification society because of possible deleterious effects on the steel deck. Satisfactory decking is produced only when specific materials are properly applied. For this reason, it is generally the practice of many shipyards to assign the responsibility of the deck-covering installation to one subcontractor who both supplies and installs all the material. The shipyard would limit itself to the preparation of the steel surfaces.

In the following paragraphs, a brief description is given of the various deck coverings and their application, as well as a table of approximate installed weights for each type, plus a table of suggested locations. New developments in special non-skid lightweight materials, for deck coverings, are continually being made with resulting improvement in appearance, wearing characteristics and reduced weight. Typical details are shown in Figure 22.45 .

22.8.2 Wood

Today, wood decking is only used on cruise/passenger ships for enclosed promenades and in passenger weather deck areas. From the point of view of appearance and comfort, wood is considered the most desirable deck covering. However, even other compositions are being used in place of wood. Classification societies permit slight reductions in superstructure plating thickness where wood sheathing is applied. On cruise ships and special craft with large superstructures however, the weight and fire protection problem has made it necessary at times to prohibit wood in enclosed spaces in favor of lightweight mastic decking, which are described under Lightweight Outdoor Decking.

In spite of its limitations and high initial cost, wood decking is still considered superior and probably will continue as the preferred weather deck covering for cruise ships which operate in the tropics, where tiling and plastic compositions in the vicinity of swimming pools and on sun-decks become unbearably hot.

22.8.3 Magnesite

Magnesite, once the most common decking in crew quarters on cargo ships, is no longer in favor, having been supplanted by tiling material, which has been found more attractive in appearance and easier to clean. Magnesite is still used as an underlayment and as fire insulation, but a suitable tile or other covering, not exceeding 10 mm in thickness, is applied over the underlayment for finish purposes.

22.8.4 Terrazzo

Synthetic Terrazzo is a thin-set deck covering. Conventional Terrazzo is not being used anymore due to its labor intensive finishing requirements. The synthetic Terrazzo is either of latex or vinyl base and easy to install. It has excellent decorative properties, as well as being of low fire hazard; it has excellent adhesion, and is economical to maintain. It is applied in thicknesses of 6 to 13 mm. Terrazzo is used extensively in all wet spaces, passages, swimming pool beaches, and, occasionally in crew staterooms. A cast variety of this material is often used for flooring in shower stall spaces. A special type of non-conductive synthetic terrazzo is used in hospital spaces.

22.8.5 Ceramic Tiles

Ceramic tiles of various kinds are widely used as finish deck coverings in the custom built onboard wet spaces listed in Table 22.m. Today, with modular toilets the deck is fiberglass, as is the rest of the enclosure. In spaces requiring frequent wash-down (such as galleys), square quarry tile/red-grooved, ribbed back is used. Quarry tile has extraordinary wearing qualities, is non-slip, and has proved to be highly successful in service.

Cove tiling is fitted at bulkheads and curbings. The underlayment is required to be somewhat higher than the minimum in order to obtain satisfactory slope for drainage to gutter ways.

For this reason, some designers prefer cement to a thickness of about 44 mm in preference to building up excessive thickness of the latex type underlayment.

Ceramic non-slip tile, 6 mm thick, is used extensively and is very satisfactory in service. It may be hexagonal or square and of various colors which may be worked into pleasing patterns by the interior decorator.

Table 22.III Typical Selection of Deck Covering Materials

Space	*Material*	*Comment*
PASSENGER AREAS		
Dining room, foyers	Vinyl tile, rubber tile	Some owners prefer carpeting
Theater, library	Carpet	Quiet lounges
Staterooms	Vinyl tile, carpet	
Bathrooms	Ceramic tile, terrazzo	Built onboard spaces, modular fiberglass with non-skid pattern molded in
Stairs and landings	Vinyl tile, rubber tiless	
Passageways	Ceramic tile, rubber tile	
Swimming pool tank	Ceramic tile, fiberglass	
Swimming pool beach	Ceramic tile, terrazzo	
Weather decks	Wood-latex	
Enclosed promenade decks	Wood, molded rubber tile	
CREW SPACES		
Staterooms and passageways	Vinyl tile, terrazzo, carpet	Owners' preference
Lounge	Vinyl tile, carpet	Owners' preference
Recreation spaces	Vinyl tile	
Galleys, pantries	Quarry tile, ceramic tile, terrazzo	Owners' preference
Laundries	Terrazzo, ceramic tile	
Wet service spaces (lockers)	Terrazzo, ceramictile	
Dry service spaces (linen lockers,baggage rooms)	Gratings on painted steel deck	

22.8.6 Rubber Tile and Sheet

Rubber tile, available in three thicknesses, 6, 5, and 3 mm, forms a decorative covering, is very resilient, and has a smooth surface and dull gloss. A wide variety of designs are p~sible because the material is laid in individual blocks or tfIes. It resists the action of water for cleaning but is not intended for prolonged immersion. It has excellent abrasive qualities and is long wearing. For large public spaces, sheet rubber with good service characteristics may be used to make a less expensive installation, lending itself to decoration by inlays. Rubber coves of dark color usually are fitted around the deck boundaries of all spaces where rubber tiling or sheeting is fitted. The cove can be eliminated in all spaces, except public rooms, by using stainless steel or nonferrous metal baseboards. Sheet rubber tile is often used in hospital spaces.

22.8.7 Vinyl Tile

Vinyl tile is the most widely used of all finished deck covering on all types of ships. There are various types, the best of which is a homogeneous vinyl, 3 mm thick available in plain, marblized, or terrazzo-effect colors. Due to its dense surface, it is easy to maintain. A rubber or vinyl-set cove is used in the periphery of the space, available in 100 or 150 mm height. Laminated vinyl tile is a thin veneer of vinyl laminated to a backing: It is also available in 3 mm total thickness, has decorative qualities comparable to homogeneous tile and is more economical but is not as long wearing. A lightweight fire-retardant type of vinyl asbestos tile, 2 mm thick, used mainly on naval ships, also is available.

22.8.8 Carpeting

On both passenger and cargo ships, carpeting is used extensively in both staterooms and public rooms. Carpeting is usually fitted wall-to-wall over latex underlayment where no fire protection requirements exist or over the required thickness of approved deck covering where required for fire control. Carpeting is used extensively in public spaces and also in dining rooms, main stairways, and passageways. In some instances, carpets and padding must be of wool, or other fire resistant materials, approved by the regulatory body.

During foul weather at sea and during in-port periods when the ship is crowded, carpet runners, cocoa mats, rubber matting, and the like are often rolled out in traffic areas.

22.8.9 Lightweight Outdoor Decking

As mentioned in the description of wood decking used aboard large *cruise ships* with extensive superstructures and weather decks, stability considerations have led to development of lightweight decking for enclosed promenades and weather decks. A corrugated rubber tile has been developed for closed promenades, which is constructed of units approximately 760 mm square, subdivided into smaller squares by grooves of uniform width and depth. The overall effect resembles a continuous sheet of rubber flooring because the grooves coincide in both directions. These installations have proved successful and have eliminated the need for constant cleaning, planing and caulking of wood decks. In weather areas, a lightweight aggregate in rubber-latex, in common use on large naval craft, has been used as a substitute for wood decking. It is resilient, adheres well to steel, is waterproof and weatherproof throughout the weather temperature range, is very light in weight, will not burn, and is non-slip whether wet or dry. It is available in fast colors and lends itself to markings for deck games and directional signs.

Other types of trowel-on finished decking recently developed, offering lightweight and good appearance, are vinyl plastics, magnesite with terrazzo mixture, latex with marble chips providing a terrazzo finish, and other combinations to produce various finishes.

TABLE 22.IV Underlays for Deck Covering

Latex mastic	8.5 to 12.2 kg/m^2 for 6 mm thick
Magnesite scratch coat	13.7 kg/m^2 for 10 mm thick
Portland cement	61 kg/m^2 for 25 mm thick
Asphalt emulsion	12.2 kg/m^2 for 6 mm thick

Note: The weight of underlayment chosen must be added, per Table II

TABLE 22.V Installed Weight of Deck Coverings

Magnesite	22.0 kg/m^2 for 10 mm thick
Latex mastic	12.2 kg/m^2 for 6 mm thick
Latex	14.6 kg/m^2 for 6 mm thick
Sheet rubber or rubber tile	7.3 kg/m^2 for 33 mm thick
Ceramic tile (Cove 2.34 kg/m^2, 100 mm high)	13.4 kg/m^2 for 6 mm thick
Vinyl tile, homogeneous	9.3 kg/m^2 for 3 mm thick
Vinyl tile	8.5 kg/m^2 for 3 mm thick
Quarry tile	41.5 kg/m^2 for 19 mm thick
Mastic finish refrigerated	Abt. 73 kg/13 mm thick spaces

Note: The weight of underlay chosen must be added, per Table II

22.8.10 Underlayment

For interior deck coverings, it is necessary to use underlayment under the finished covering for the purpose of smoothing out surface irregularities of the steel. Welded decks are seldom smooth enough to make a satisfactory surface for resilient coverings. When resilient deck coverings have been cemented directly to steel without underlayment, a drumming sound is caused by foot traffic. Humps and hollows are magnified, particularly when the finished deck has a polished surface, and changes in temperature tend to deteriorate the adhesive cement with which the deck coverings are bonded.

The underlayment used is of the plastic, trowel-on type in the following categories:

- those with magnesium oxychloride as a binder, commonly known as magnesite underlayment;
- asphalt emulsion as a binder, known as emulsion underlayment;
- liquid latex (rubber) binder, known as latex underlayment.

Of these three underlayment categories, the magnesite type requires welded clips or wire mesh for attachment with an average thickness or 19 mm and a minimum of 13 mm. It is heavier than the others but cheaper than the latex type. The asphalt-emulsion type does not require anchoring clips if the steel surfaces are thoroughly cleaned of mill scale, oil, grease, etc., and may be applied to a minimum of 10 mm thickness. The latex type has come into general use because of its lightweight, good bonding quality directly to steel, and relatively small thickness required. Generally, a 10 mm thick underlayment will suffice for most installations. It is highly resilient, and was originally developed and used extensively on naval ships. It is used as a backing for tile, carpeting, magnesite, and all of the deck covering material described herein. Whenever evaluating materials for deck coverings, consideration must be given to Coast Guard fire protection regulations, as they place specific limitations or thicknesses and locations of combustible deck covering materials aboard some vessels.

The underlayments for all finished deck coverings are listed in Table 22.IV. Table 22.V gives the installed weight of various types of deck coverings, including the underlay used, thickness, etc.

22.9 JOINERWORK, INSULATION, AND LININGS

22.9.1 General

Joinerwork is the term generally applied to those materials used for the construction of the finished interiors of compartments. Bulkheads, especially in accommodation areas, generally consist of joinerwork, which provides livable, workable, decorative spaces. Such bulkhead panels, linings and ceilings with their connecting devices form the joinerwork of a compartment. *loinerwork bulkheads* separate rooms for each other and rooms from passageways. *Lining* is the sheathing in way of structure such as the superstructure or deckhouse sides, bulkheads and casings. It is also the name for sheathing over insulated structure in both general spaces as well as refrigerated storerooms. *Ceiling* is the overhead system that finishes out the cabin or public space. Joinerwork includes *joiner doors* and their frames.

The current use of noncombustible materials in ship construction, in place of wood, involves a variety of materials such as inorganic composition panels, metallic core section materials clad with decorative board, light gage steel plates and shapes, and decorative hard and soft plastic laminates of specified thickness and fibrous insulation. Joinerwork thus involves a complex collection of materials grouped together primarily because they have replaced wood. Joinerwork, originally a means of subdividing a ship for reasons of utility or privacy, nowadays is integrated into the design for fire protection (see Chapter 16 - Safety).

The most important regulations affecting joinerwork deal with fire safety measures. Both the individual regulatory bodies and SOLAS exert a dominating influence in specifying the locations for and types of structural fire protection and in defining the materials, which may be used.

J

22.9.2 Joiner Bulkhead, Lining and Ceiling Systems

Today, there are a number of completely integrated systems that provide all the bulkhead, lining and ceiling required in a typical merchant ship. There are many proprietary lining and ceiling systems for accommodations and Figure 22.46 shows the details of some of these. Modular toilets for crew and officer cabins are now the norm (Figure 22.47). **In** the case of cruise ships there are special cabin modules built on shore, from joinerwork systems including all the furniture and toilets, and installed in the ship as a complete unit (Figure 22.48).

Today, it is quite common for shipyards to purchase fully outfitted deckhouses from companies specializing in this area. They may even give a complete turnkey contract to the company, which becomes responsible for the design and construction of the complete deckhouse structure, the joinerwork, furnishings and steward/commissary outfitting (Figure 22.3).

22.10 FURNITURE, FURNISHINGS, AND STEWARD OUTFIT

22.10.1 General

That part of the hull outfit which pertains to the outfitting of the living spaces in a vessel is often treated under the heading of *furniture and furnishings* which would include not only the berths, tables, dressers, desks, sofas, chairs, etc., but also bedsprings and mattresses, upholstery, cushions, curtains, mirrors, wastebaskets, lamps, curtains and miscellaneous fittings. Also pertaining to the living quarters are items such as bedding (sheets, blankets, pillowcases, towels, etc.), which are often referred to as items of *stewards outfit* which term would also include the commissary equipment contained in the galleys, pantries, sculleries, dining rooms, and mess rooms.

22.10.2 Furniture

Furniture for passenger, officer and crew accommodation is usually of steel, aluminum, composite with veneer, or hardwood with exposed hardware of stainless steel, bronze, brass or anodized aluminum. Metal case goods are often insulated with a mineral base material at least 1.5 mm thick.

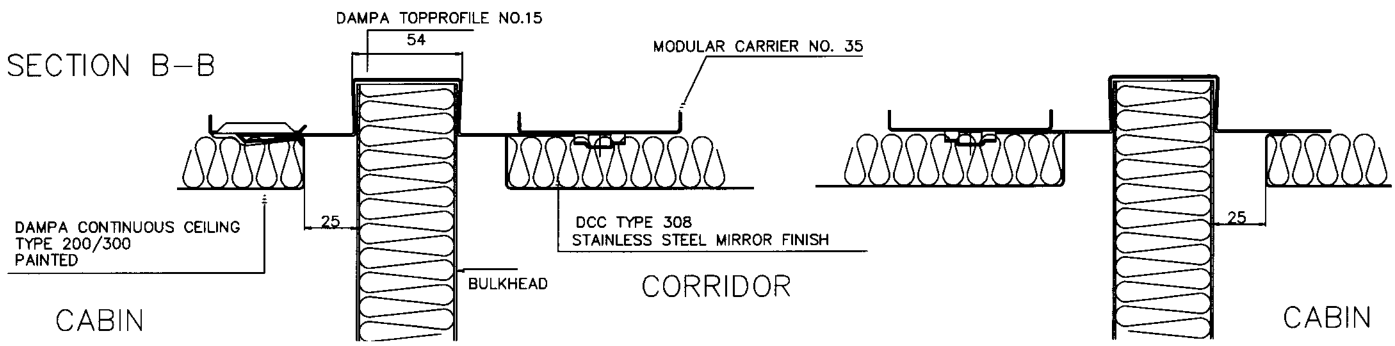


Figure 22.46 (a) Typical Joiner Linings and Ceiling Details—Ceiling details (DAMPA)

All furniture except chairs is secured to decks or bulkheads and portable furniture should have securing devices for lashing down. Drawers should have positive means to prevent opening in heavy seas. Resin laminate (such as melamine) tops on tables, dressers, and desks, is often specified for scratch, burn, and liquid resistance.

There are still some shipyards that have their own carpenter shop, which makes the furniture for the ships they build. However marine furniture is usually a purchased item from companies around the world that specialize in manufacturing and often installing marine furniture, especially for cruise ships. Figure 22.49 shows typical marine furniture.

22.10.2.1 Cabins

Furniture in staterooms is usually of metal with dresser table and desktops of resin laminates. In general upholstered stateroom furniture has self-supporting spring construction. Upholstery coverings of synthetic leather of selected colors are typical. Cushions of neoprene (latex foam) are in gen-

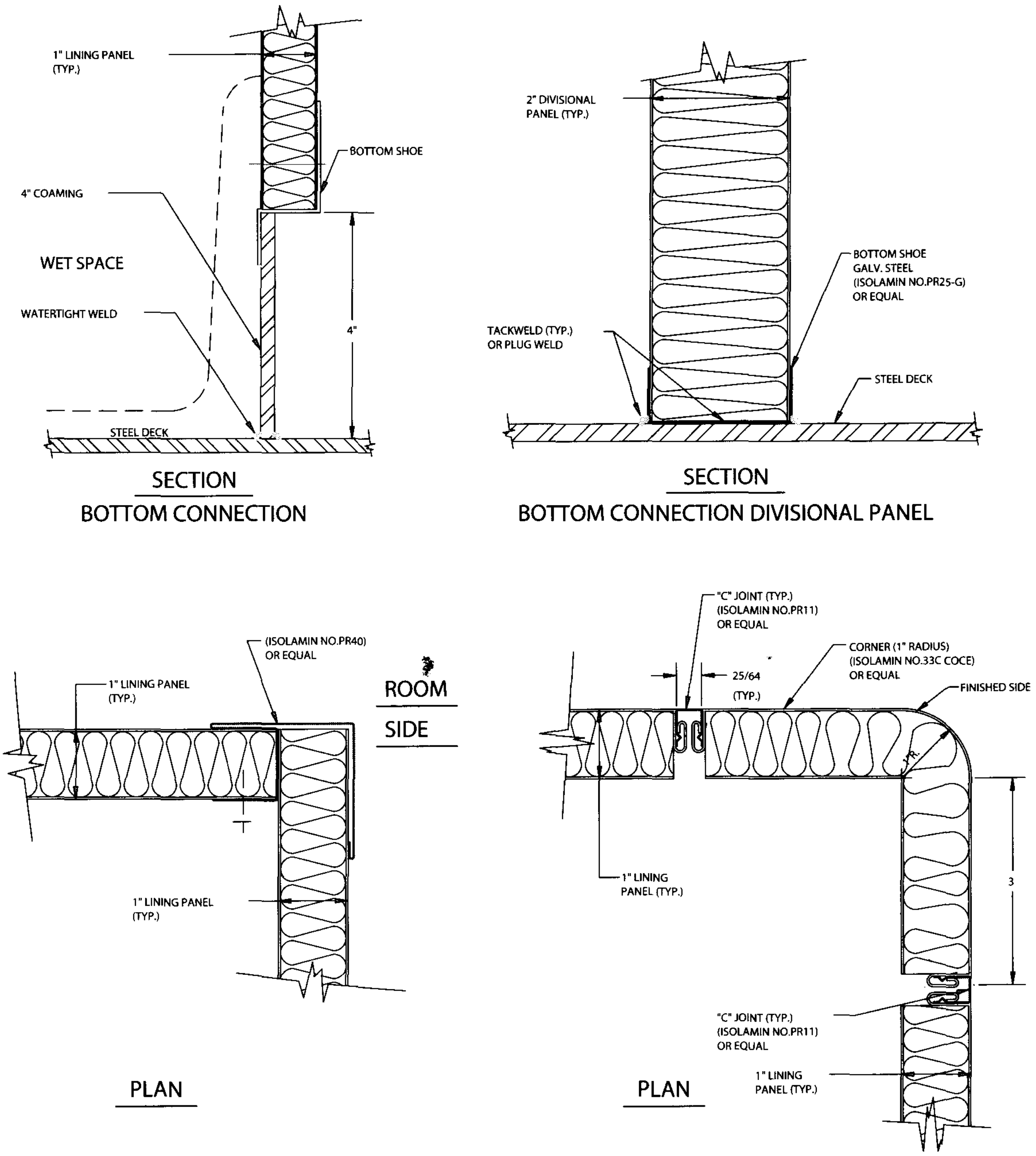


Figure 22.46 (b) Typical Joiner Linings and Ceiling Details—Joiner Bulkhead and Lining Details

eral use. Wardrobes for passengers, officers and crew should be of full deck height, often built in. Berth lights, desk and table lights are provided in all rooms, where appropriate.

The furniture in typical cabins is shown in Figures 22.6 and 22.7.

22.10.2.2 Public rooms and offices

This category includes dining rooms, lounges for passengers, officers or crew, recreation rooms, and offices. For public rooms in passenger ships see Chapter 37 - Passenger Ships.

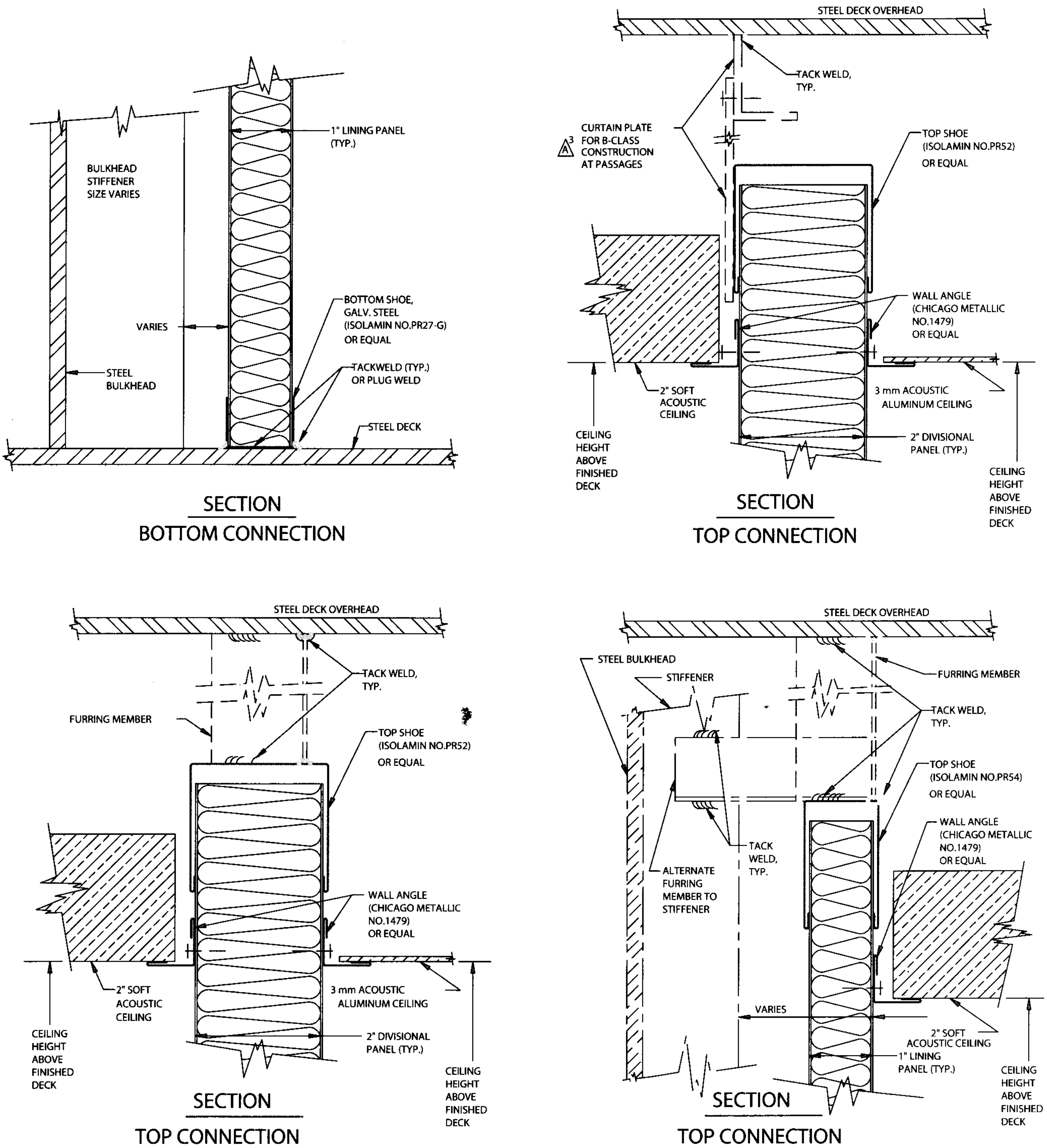


Figure 22.46 (b) (continued) Typical Joiner Linings and Ceiling Details—Joiner Bulkhead and Lining Details

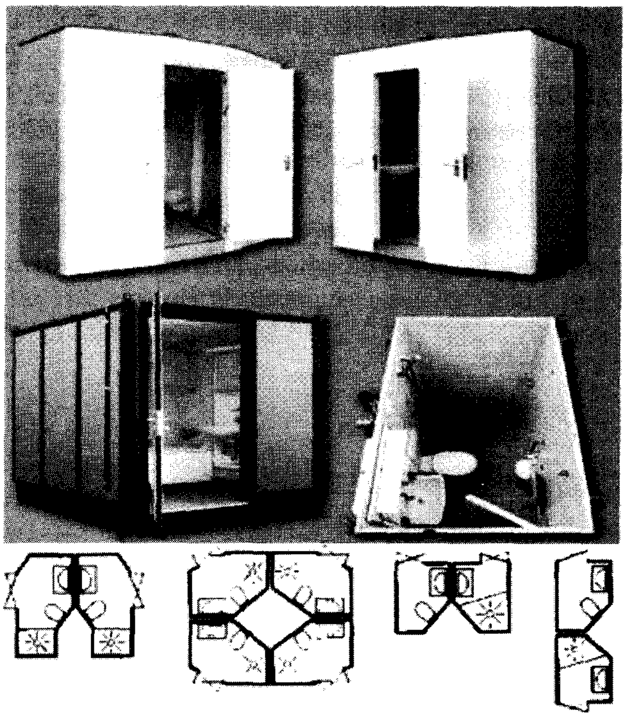


Figure 22.47 Modular Toilets

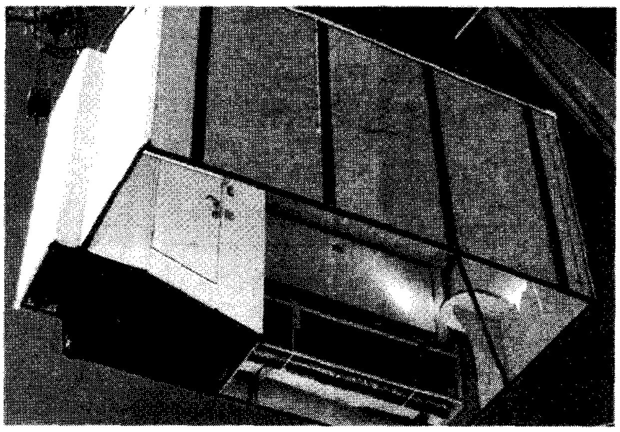


Figure 22.48 Modular Cabin

The captain and chief engineer are often provided with offices where ship's business can be transacted and visitors or officials entertained, although today the dayroom and the office are usually combined.

A ship's office and an engineer's office are often provided adjacent to the first mate's and the first assistant engineer's offices, respectively, with typewriter desks and often with plan desks (suitable for spreading out long plans). The steward's department office when provided should be similar to these.

22.10.3 Upholstery, Draperies, Carpeting

Decorative fabrics, similar to those found in corresponding spaces in an office, private home or hotel, are installed aboard ship, as follows:

22.10.3.1 Upholstery

Sofas, lounge, easy chairs and, if required, ordinary chairs are either upholstered with cloth or artificial leather. In general, cloth coverings are provided in passenger and senior officer's compartments and artificial leather in junior officer's and crew rooms. Upholstered furniture usually has self-supporting spring construction with a horsehair covering and on top of this a protective covering and the upholstery. Cushions are nowadays of neoprene or latex foam. Other top quality materials are used and loose cushions, where specified, are usually made reversible.

22.10.3.2 Curtains

Curtains are used at sidelights, windows, baths and showers. In some cases special blackout curtains or blinds are used in certain locations on the fronts of houses to prevent the radiation of light into the wheelhouse. Curtains in most locations are made of single fabric but are often lined in passengers' and senior officers' quarters. Bath and shower curtains are made of plastic. Curtains are supported on rods with fittings and rings. Chart rooms and other spaces, which are fitted with special blinds of the roller type to prevent light reflections, are often provided with regular curtains in addition for a more pleasing appearance. Curtain materials are usually selected with an inherently fireproof quality or are treated to be fire resistant.

22.10.3.3 Carpeting

Floors of passenger, crew, and certain public spaces are generally covered with carpet either fitted wall to wall or laid loose in individual areas but in both cases they are secured to the deck by special fasteners. Wool carpeting has proven most fire resistant but is now becoming relatively too expensive for marine applications so that synthetic materials equivalent to wool in fire resistance are now in general use.

22.10.3.4 Linen supplies

The shipowner and not the shipbuilder normally provide the bedding, including sheets, pillows, pillowcases, blankets, towels, etc., as an *owner furnished item.* Standards used by individual shipping companies can vary depending on quality desired. Normally these would be equal to first class shore hotel standards often with special requirements as to company insignia, etc.

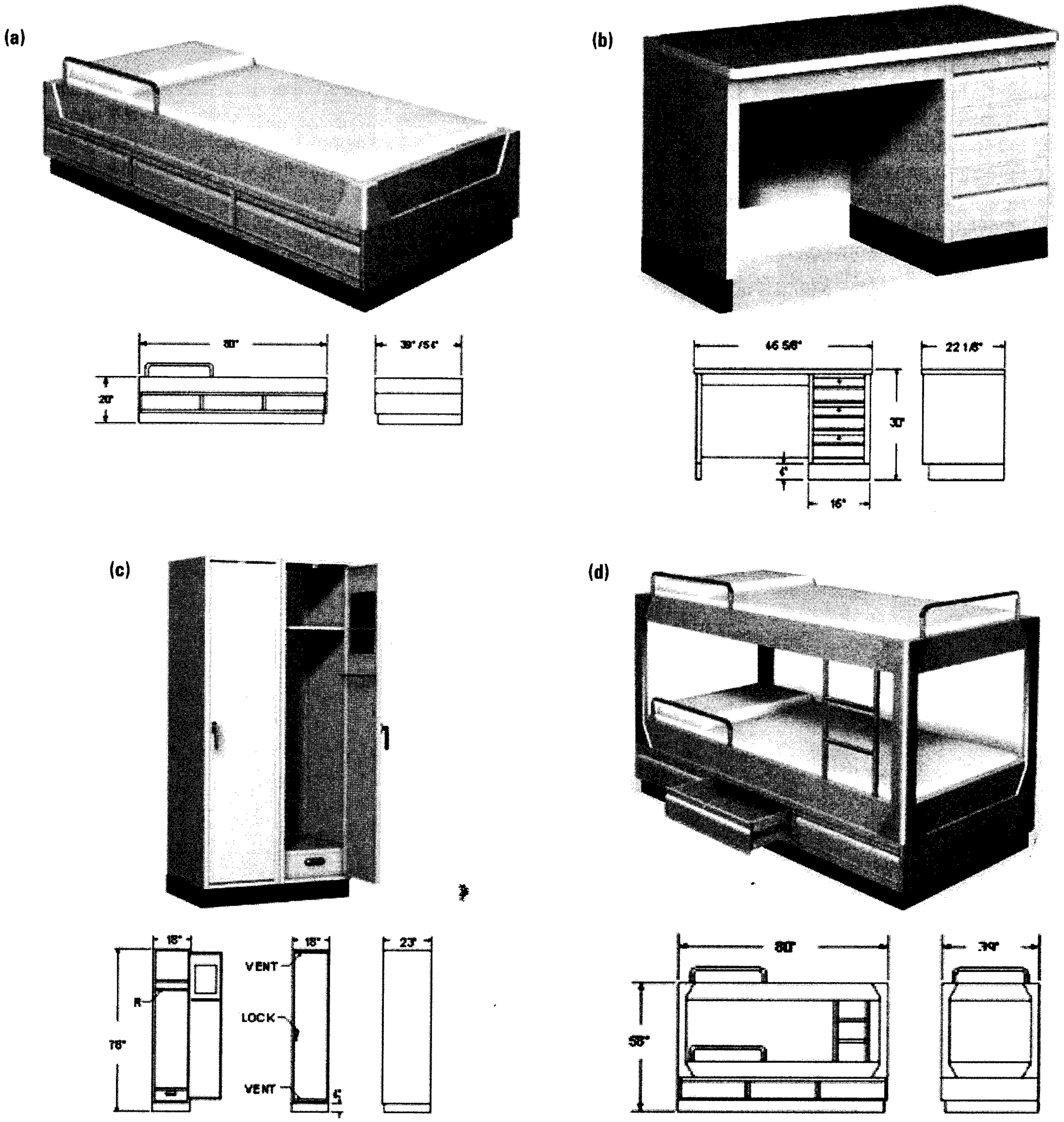


Figure 22.49 Typical Ship Crew Furniture. a) Single Berth. b) Desk. c) Locker. d) Double Tier Berth.

22.10.4 Commissary Equipment

One of the most important functions covered by the steward's department includes spaces such as galley, bakery, pantries, and storerooms.

22.10.4.1 Galley

On most cargo vessels a single galley provides food for passengers (if carried), officers, and crew (Figure 22.50). Particular emphasis in the design and layout of all commissary spaces, particularly the galley, usually has to be made to the country of registry health service requirements. Good commercial design of equipment, modified to suit shipboard conditions is needed. Most equipment and all surfaces coming into contact with food and drink should be of CRES material and special attention should be paid to the design of all equipment to prevent the lodgment of grease and food particles in comers, cracks and joints so as to contribute to the maintenance of sanitary conditions.

Typical equipment would consist of the following:

- food self-serving tables with hot and chilled compartments and sneeze screens
- racks for pots, dishes, cups and glasses,
- refrigerators for ready-use food and food awaiting cooking after removal from reefer stores,
- shelves for general storage in the open,
- overhead cabinets for general storage with hinged or sliding doors and sectional removable shelving,
- tilting bins for storage of flour, rice and sugar.
- electric range with hot plates,
- electric ovens,
- electric convection oven,
- electric griddle,
- fry kettle,
- combination steam cooker/kettle,
- pressure cooker,
- stainless steel tilting kettle with electric steam generator,
- food mixer,
- meat slicer,
- dough proofer built into baker's dresser,
- garbage disposer, and
- baker's scale.

In the scullery area:

- dishwasher,
- garbage disposer, and
- sinks

Sinks should be of CRES material and of sufficient number to handle manual washing procedures (including water heaters for sterilization purposes) in case of temporary

Figure 22.50 Typical Commercial Ship Galley

breakdown of automatic dish washing equipment. A separate lavatory should be provided for galley staff for hand washing purposes.

Steam serving tables are provided complete with hot water pans for keeping meats and vegetables warm or, alternatively, dry heat (electric) hot food tables.

22.10.4.2 Pantries and serveries

Pantries are normally located adjacent to the dining room and serveries adjacent to crew mess rooms and provide a station where food can be received from the galley (often via a dumb waiter when on different deck level to the galley) and from there served to the dining or mess room. There are often facilities in the pantries and/or the mess rooms, for cooking snacks or serving simple meals to those on watch outside of normal galley hours. Pantries usually contain a refrigerator, hot plates, coffee maker, toaster and warmer units or a steam table with inserts for meat pans plus racks for dishes, cups and glasses and sinks. A recent arrangement is to provide a serving space adjacent to the galley with buffet style serving for the crew. The serving space should have two fireproof doors to facilitate access into the servery and out to the mess room. The bulkhead between the servery and the mess room must be fireproof.

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Chapter 23

Ship Preservation

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23.1 INTRODUCTION

The purpose of this chapter is to present the principles of ship preservation system selection and application.

The primary purpose of ship preservation is to reduce life-cycle operating costs of the ship by preventing or reducing degradation of the ship's structure, systems, and components which tend to occur as a result of using refined metals in a corrosive environment. Secondary reasons for using preservations include maintaining desired appearance, minimizing abrasion damage, and reducing fouling of the underwater hull.

23.2 GENERAL PRINCIPLES OF CORROSION AND CORROSION CONTROL J

The cost of corrosion to an industry is difficult to determine accurately. Probably the most extensive effort to date to determine the cost of corrosion was performed in 1978 by the Bureau of Standards and Battelle Columbus Laboratories and updated in 1995. This study, which was not industry specific, estimated the total cost of corrosion to the United States economy was 350 billion dollars, or about 4.2% of the Gross National Product (GNP) using 1995 data. This high cost is not totally preventable for two primary reasons. First, it is not practical to eliminate all corrosion. Second, it is often significantly more cost effective to reduce corrosion rather than eliminate corrosion (in those rare cases where elimination is practicable). The economically preventable cost due to corrosion is estimated at between 25% and 33% of the total cost of corrosion.

The goal of ship design and construction is not to produce a vessel free of corrosion, but to produce a vessel that reduces corrosion in a cost effective manner through, in most cases, traditional methods of corrosion control, recognizing that corrosion control decisions may be secondary to other decisions. The best example of the secondary level of importance associated with corrosion is material selection for structural components. The factors involved in the selection of structural components include material properties, ease of use in production, availability, and cost (1,2). Material properties include strength, strength to weight ratio, ductility, fracture toughness, and corrosion resistance. Of these factors, corrosion resistance of the material is frequently not a prime consideration for two reasons. First, making corrosion resistance in a marine environment the most important factor in selecting structural materials would make most shipbuilding cost prohibitive. Second, corrosion resistance can be addressed by methods other than the selection of corrosion resistant materials, such as the use of specific coatings. For these reasons, the material used for the vast majority of marine vessel hull and other structural components is carbon steel which is prone to severe corrosion in the marine environment, has moderate strength, but is easily fabricated and has relatively low costs. Aluminum alloys, which have significantly lower corrosion rates than carbon steel in a marine environment, are sometimes selected for use in small craft and high performance craft not for it's corrosion resistance, but for it's higher strength to weight ratio. Both steel and aluminum alloys rely on coatings to prevent or reduce corrosion in the marine environment.

23.2.1 Corrosion Theory

23.2.1.1 Definition

Corrosion is most frequently defined as the degradation of a material, usually a metal, due to interaction with its environment. It is difficult to totally eliminate corrosion in the marine environment for two reasons. First, the inherently corrosive nature of seawater, and second, most materials used for engineering applications, including steel and aluminum, are thermodynamically unstable. Most metals are found in nature in the form of oxides and hydroxides. In the refining process, energy is expended to convert these naturally occurring ores to the elementary metal forms that are used in industry. The refined metal is unstable, or, more correctly, meta-stable, compared to the naturally occurring oxides and hydroxides. This provides the thermodynamic driving force to the corrosion process.

23.2.1.2 Electrochemical nature of corrosion

Nearly all corrosion reactions in the marine environment are electrochemical in nature, i.e., electrical current is associated with the chemical reactions of corrosion. The driving force of corrosion can be considered the electrical potential difference between two states of matter. In most marine corrosion processes, electrical current passes between two sites (an anode and a cathode) through an electrolyte (seawater), with associated reactions at both the anode and cathode. The reaction at the anode is the corrosion reaction, called oxidation.

There are several requirements for electrochemical corrosion to take place. There must be an anode and cathode, both must be in contact with a common electrolyte, there must be an electrical connection between the anode and cathode, other than the electrolyte, and there must be a thermodynamic tendency for electrochemical reaction(s) to occur. If these requirements are present, corrosion will occur. Eliminate anyone of these elements, and corrosion will not occur. These requirements are shown schematically in Figure 23.1.

23.2.1.3 Forms of corrosion

While there is no single agreed method of grouping the various types and forms of corrosion, those listed in this section are in reasonable agreement with most acknowledged corrosion experts (3-6) and are presented in a manner that is easily understood.

Galvanic corrosion is the form of corrosion most easily understood and occurs when dissimilar metals are in electrical contact and in an electrolyte forming the electrochemical cell shown in Figure 23.1. For example, if nickel is in electrical contact with steel, and both are wetted or immersed by a common electrolyte, oxidation (corrosion) occurs on the steel, whereas reduction (and no corrosion) occurs at the nickel site. The steel, being more active, corrodes, whereas the nickel does not corrode. This is the principle of sacrificial anode cathodic protection discussed later in Section 23.2.2.

In a strictly technical sense, all common forms of marine corrosion are galvanic corrosion in that corrosion occurs because of an electrochemical reaction between an anode and a cathode. The metallurgical attribute that causes or allows the anode and cathode sites to be formed is how corrosion is categorized.

General corrosion occurs somewhat uniformly over the surface of a single metal, such as steel. The anode and cathode are created by electron density differences at the atomic level; with one region having a higher density of electrons than an adjacent region providing a potential difference and thus the driving force for oxidation and reduction reactions. Other forms of corrosion arise when slight differences in the environment, as in crevice corrosion and pitting, or metallurgy, as in intergranular corrosion and de-alloying, cause the slight potential difference needed to start the corrosion process. Environmental assisted cracking, which includes both stress corrosion cracking and hydrogen embrittlement, is a form of corrosion that requires stress along with a specific ionic species. For example, for stress corrosion cracking of brasses to occur, ammonium ions and a tensile stress are required. Finally, stray current corrosion is corrosion caused by the unwanted passage of electrical current. Referring back to Figure 23.1, the oxidation of the anode occurs when current passes from the anode into the electrolyte. Current merely passing through a metal, as in a copper wire, or even a copper-nickel pipe, does not cause corrosion. Corrosion occurs only when current exits the metal and enters the electrolyte.

Anodic or Less Noble (Corrodes)
Magnesium
Aluminum
Zinc
Cadmium
Iron or Steel
Stainless Steels (active)
Soft Solders
Tin
Lead
Nickel
Brass
Bronzes
Nickel-Copper Alloys
Copper
Stainless Steels (passive)
Silver Solder
Silver
Titanium
Gold
Platinum
Cathodic or More Noble

Figure 23.2 Galvanic Series

23.2.1.4 Galvanic series

A galvanic series is a listing of metals and alloys in order of relative activity in a given environment. An example of a galvanic series for flowing seawater is shown in Figure 23.2. Some galvanic series also provide the potential, or potential range, of the metals listed, but this is not a requirement. The primary utility of a galvanic series is predicting which metal in a pair of metals will suffer from galvanic corrosion, and which will be cathodically protected. To use a galvanic series, you must note the noble (cathodic) end of the series, or conversely, the active (anodic) end. Relatively inert metals such as gold and platinum will identify the noble end, if the series is not labeled, and common active metals such as zinc and magnesium will identify the active end.

For any given pair of metal listed in the series, the metal closer to the active end will galvanically corrode, while the metal closer to the noble end will be cathodically protected.

Although useful for predicting which metal will corrode, the galvanic series should not be used to predict the rate of corrosion. Rates are dependent on the kinetics of the electrochemical reactions, while the galvanic series is based on thermodynamics. Attempts to use the galvanic series to predict corrosion rates often result in erroneous decisions.

23.2.2 Corrosion Control Methodologies

For the purposes of this chapter, methods for controlling corrosion are grouped into five categories. While not universal, these categories are commonly found with only slight modifications by most corrosion control references (3,5,7). The five methods of controlling corrosion are material selection, design, barrier coatings, cathodic protection, and inhibitors. In discussing each of these methods, the reader should recall the requirements of corrosion described in Section 23.2.1, and consider the principle that if one or more of these corrosion requirements are affected, the corrosion reactions are also affected.

23.2.2.1 Material selection

Material selection is choosing a material for the specific environment and application so that the resultant corrosion, if any, is maintained within acceptable limits. *Acceptable limits* is determined by the ship owner and designer, and may allow for periodic replacement of a part or component over the lifetime of the system for economic reasons. Take, for example, copper-nickel (CuNi) alloys which are often used for seawater piping systems. CuNi has relatively low uniform corrosion rates (typically less than 25 ,.un/yr, or 0.001 inches (mil) per year (mpy)), but may be subject to localized erosion corrosion and pitting, at sharp bends and under deposits respectively, which may require replacement of piping system components. CuNi's susceptibility to localized erosion and pitting, however, is usually preferred over the alternative of upgrading the piping material to a more corrosion resistant material, such as inconel or titanium.

Most materials considered corrosion resistant, especially to seawater environments, do in fact corrode, but do so in a manner that results in very low corrosion rates. This is due to the formation of thin, tightly adherent compounds, often oxides, that effectively eliminates further corrosion. Materials that gain their corrosion resistance through the formation of these passive films, as they are called, include aluminum, stainless steels, and nickel-chromium-molybdenum alloys.

23.2.2.2 Design

Designing for corrosion control addresses factors that can lead to corrosion such as eliminating crevices, eliminating standing water, allowing for drainage, and also includes providing allowances for corrosion. The latter is frequently considered for seawater piping, including the CuNi material previously mentioned.

23.2.2.3 Barrier coatings

Barrier coatings act by physically separating the metal from the effects of the environment (electrolyte) thus remm;ng an essential factor for corrosion. All coatings act as a barrier to some extent, but some coatings act only as a barrier. Barrier coatings include greases and oils, as well as common organic coatings (paints).

23.2.2.4 Cathodic protection

Cathodic protection is an electrical technique, which uses, in the natural method, a more active metal to protect the ship's structure or component. The more active metal is placed in electrical contact and in the same electrolyte with the metal to be protected. The active metal becomes the anode of the electrochemical cell and corrodes, the site of the oxidation reaction, while the structure to be protected becomes the cathode. This natural form of cathodic protection is called sacrificial anode cathodic protection since the active metal sacrifices to protect the structure. The active, sacrificial metal may be provided in the form of a sacrificial anode, or may be incorporated into the chemistry of coating such as in zinc rich coatings. In the other method of cathodic protection, commonly called impressed current cathodic protection, the active metal is replaced by a direct current (DC) power source that serves to make the structure the cathode. Cathodic protection and coatings are usually recommended to be used together for corrosion protection of immersed components and structures, such as underwater hulls, external propulsion gear, and ballast tanks.

23.2.2.5 Inhibitors

Inhibitors are substances that, when added in small quantities to the environment, inhibit one or more of the steps in the corrosion process. Inhibitors are commonly used in three ways. First, inhibitors are used in closed loop fluid systems, such as boiler steam systems and automobile cooling systems, where the concentration of inhibitor in the liquid can be maintained. Second, inhibitors are used in the form of Vapor Phase Inhibitors (VPI) to reduce atmospheric corrosion in closed spaces. Third, inhibitors are used in coatings.

In practice, the methods of material selection and design are best accomplished before the system or component is fabricated. The last three methods (barrier coatings, cathodic protection, and inhibitors) are employed after fabrication is completed, and often in combination. For example, as just mentioned, coatings may contain inhibitors to either supplement or replace the barrier function of the coating. Similarly, coatings may employ sacrificial cathodic protection, usually in the form of zinc dust or zinc flakes, to improve the corrosion protection of the structure.

23.2.3 General Preservation Principles

23.2.3.1 Coatings and coating types

A coating is any material that will form a continuous film over a surface; whereas paint refers to a general type of coating in which a mixture of pigment and vehicle together form a liquid or paste that can be applied to a surface (8), and is organic in nature. Coatings is a broad category that includes paints (organic coatings), as well as inorganic metallic and non-metallic coatings.

The components that make up an organic coating are resins, pigments, fillers, and solvents. Resins are solid or semi-solid products with no definite melting point, and are generally of high molecular weight. Pigments are additives such as coloring agents and inhibitors. Fillers increase the bulk of the coating, improve density, and can improve abrasion resistance. Solvents are often used as the dispersing medium, which transport the other components to the substrate, and may play a role in the drying and curing of the coating. Two other terms that will be used later in this chapter are curing and drying. Drying is the evaporation of the vehicle, whereas curing is the ultimate reaction of the components. Curing may be by atmospheric drying, baking (temperature activated), or catalyst activated chemical reaction.

Organic coatings are most commonly categorized by resin type, cure mechanism, or a combination of the two, but they can also be described by the major additive, and/or specialized properties.

Organic coatings include asphalt, oil, alkyd, acrylic, vinyl, epoxy, and urethane. Special purpose coatings include anti-fouling coatings and zinc-rich coatings. Non-organic coatings include concrete, glass, and ceramics, referred to as inorganic non-metallic coatings, metal coatings, and conversion coatings. This section provides only a sufficient overview of these coating types to support other section topics. A more comprehensive text such as Munger (7) should be consulted for an in-depth discussion of coating types and cure reactions:

Asphalts: Asphalts are derived from petroleum and coal residues and include natural asphalts and coal tars. Asphalts may be used alone or mixed with other materials. These coatings are typically inexpensive, heavy, and do not require extensive surface preparation. They degrade in sunlight and may not dry hard.

Oils: Oils are based on naturally occurring oils such as linseed, tung, pine, and fish oils and provide a stable film when oxygen from the air reacts with oil molecules to harden the film and produce limited cross-linking. Atmospheric drying of most oils is somewhat slow, with obvious consequences.

Alkyds: The alkyd resin (also called polyester) offers great versatility and replaced oils as the predominant easy applied coating early in the 20th century. Alkyds derive their versatility (and economy) from the variety possibll in the basic raw material (fatty acids and alcohols) from which the alkyd resin is produced. Alkyds have good color stability and are suitable for use in most atmospheric and mildly industrial environments, but should not be used in strongly acidic or alkali conditions.

Acrylics: There are two major categories of use for the acrylic resin. First, acrylic resins are used in conjunction with other resins, for example, epoxies and vinyls, to improve appearance in exterior applications, and second, acrylics are used in the preparation of latex water based paints. Latex paints are used extensively for interior applications where appearance considerations are equal to or exceed durability requirements.

Vinyl: Vinyl coatings are based on the same molecule as common PVC (poly-vinyl-chloride) piping, and are extremely resistant to most organic substances such as acids, alkalis, oils, and alcohols as well as water. It should not be surprising that vinyls are one of the most widely used classes of coating in severe industrial environments, including chemical storage facilities.

Epoxy: Although the epoxy resin may be combined with oils, epoxy coatings are most often two-component coatings, in which two liquids (generally called the base and the hardener, an oil fatty acid) are mixed and chemically react to form the epoxy ester, which is an extensively cross-linked film. This extensive cross-linking results in some of the most desirable coating properties. Epoxies must, however, be mixed and applied properly, and are somewhat sensitive to the surface preparation and cleanliness of the substrate.

Urethane: Urethanes are also formed by the reaction between a base (isocyanate) and a hardener (a hydroxyl compound). Although often used for a variety of exterior and immersed applications, the properties of urethane coatings, as a class, can be varied more widely than almost any other organic coating (9).

Anti-Fouling: Anti-fouling paint is a classification by special property. Anti -fouling paints are designed to prevent the attachment and growth of biological matter on structures and hulls. This is most commonly accomplished by the incorporation of mild toxins into the coating. Tri-Butyl- Tin based toxins were very effective and popular in the 1970s and early 1980s, but usage has been restricted and now banned in most locations due to it's adverse effect on the environment. Copper compounds provide the anti-fouling ingredient in most current anti-fouling coatings.

Zinc-Rich Coatings (inorganic/non-metallic): Inorganic/Non-metallic zinc coatings utilize zinc in the coating structure. These coatings are most often used as primers, either stand-alone or in conjunction with topcoats and provide cathodic protection to the substrate.

Metallic Coatings: Metallic coatings provide a metallic layer over the substrate. The metal coating may be anodic (active) or cathodic (noble) to the substrate. In anodic metal coatings, the coating metal is less corrosion resistant (anodic) than the substrate and provides sacrificial cathodic protection, whereas in cathodic metal coatings (such as nickel plating), the coating is more corrosion resistant (cathodic) than the substrate.

The method of application is frequently used to further categorize metallic coatings. Electroplating uses electric current to deposit a thin layer of metal, usually a noble metal such as nickel or gold, onto a surface. Because electroplated coatings are applied as very thin coats, electroplating is most frequently used for non-corrosion control purposes, such as enhancing electrical connections or appearances. A molten bath is commonly used to apply zinc and other active, or sacrificial materials. Hot-Dip-Galvanizing is one common example in which (usually) small parts are dipped into a molten zinc bath and then removed, leaving a relatively thick zinc coating. Weld Cladding is used to build up even thicker layers of metal on the substrate, although this method is usually used for limited areas, such as gasket or seal contact areas. Finally, wire and flame spray can be used to apply metals to large areas of the substrate. In wire or flame spray, the coating metal (usually in the form of wire, although powder is used in some apparatus) is fed through a heat source that also propels the molten metal onto the substrate surface. Flame Sprayed or Wired Sprayed aluminum and aluminum-zinc mixtures are the most common form of metal-sprayed coatings. Metal spray coatings are usually anodic, providing cathodic protection to the substrate. Metal spray coatings tend to be very porous, requiring a sealer and/or topcoat to reduce the rapid corrosion of the metal spray. Although these coatings may be applied over various surface preparations, top performance requires optimum surface preparation (see Section 23.3). Metal sprayed coatings are not recommended for immersion of frequently wetted areas as the sacrificing of the metal spray, when it occurs, acts to rapidly undercut large areas of otherwise intact topcoats.

Conversion Coatings: These coatings convert the surface of the substrate to provide the desired affect. Processes include anodizing, phosphating, and the most common, chromating. Wash primers is a special type of chromate conversion solution, which is not actually a primer, but produces a film that provides an excellent base for most)ubsequently applied coatings.

23.2.3.2 Application methods and practices

Although there are many methods for applying coatings, three principle methods (brush, roller, and spray) dominate. Air spray uses an air stream to pick up and break up the coating into small particles and carry these particles to the substrate. Airless spray uses a pressure on the paint pot along with specially designed nozzles to produce a fine spray of the coating onto the substrate. Spray application (air and airless) provides more uniformity in coating thickness and fewer imperfections and thus is usually the preferred application method. Airless spray has several advantages over air spray including less over spray, less chance of dry-spray, and less volatiles are released to the atmosphere. Airless spray is the most common application method in today's shipyards. Brushing is probably the oldest application method, dating back to prehistory, yet remains a vital option in any painting application. Brushing is often preferred for difficult to reach areas, as well as for local touch-up. Rolling requires only marginally more skill than brushing and is often used for large flat areas.

Most other application methods are primarily for in-shop use, such as electrostatic and flame spray. In electrostatic spray, the coating particles are electrically charged and directed toward the substrate that is oppositely charged. With electrostatic spray there is little over spray and coverage is very uniform, including edges, making this a popular application method in mass production shops. Flame Spray is a technique where metals and sometimes thermoplastics are fed into a heat source (typically a flame or electric arc) where the coating is melted, and propelled to the substrate in small particles.

23.2.4 Safety Considerations and Requirements

Like all shipyard and other production shop type operations, there are safety considerations in preservation operations that if not addressed, can result in equipment malfunction, personnel injury, rework, and loss of production time. Local, States, and Federal regulations for material handling and storage, and worker safety must be reviewed and adhered to. Some of the general safety considerations that apply to all localities are discussed below.

Site Preparation: This aspect does not imply surface preparation as in abrasive grit blasting, but rather a general cleaning of the site, erection of containment, and setup of proper ventilation. Surface preparation, whether by abrasive grit blasting, power tools, or hydro blasting, has the potential to create contamination for equipment, tools, and personnel. All non-essential tools and equipment should be removed from the worksite, and permanently mounted equipment should be fully wrapped to protect this equipment from dirt, dust, water and/or paint spray. Containment is recommended for all but small-enclosed spaces to minimize the release of dirt and dust, and ventilation is obviously required for worker safety, and also to prevent the buildup of flammable vapors.

Material Storage and Handling: Many of the materials used for painting operations must be handled and stored as flammable materials. Proper personnel protective equipment (PPE) should be worn during the handling, mixing, and application of paints and coatings. Proper PPE usually implies goggles or full-face shield, respirators, gloves, and hearing protection with full face/air supplied respirators required for most abrasive grit and paint spraying operations. Spills, ifthey occur, should be cleaned up immediately. Material Safety Data Sheet (MSDS) should be provided by the manufacturer and/or supplier and should be referred to for specific explosion, safety, and toxicity requirements.

Equipment Operation: Airless paint sprayers typically operate at 6,900 kPa or greater and should be equipped with automatic or visible manual safety devices which prevent the operator from engaging the sprayer without releasing the manual safety. Alternatively, some sprayers are equipped with a diffuser nut to prevent high velocity release while the nozzle tip is removed, plus a nozzle tip guard to prevent the nozzle tip from coming into contact with the operator (9). All pressurized equipment (which includes conventional and airless spray equipment, abrasive grit blasting equipment, and water hydro blasting equipment) should be constructed following the specifications of the ASME Unfired Pressure Vessel Code and the National Board Code. Additionally, safety relief valves for all pressure equipment should be tested daily, and all should be equipped with remote control deadman valves.

23.2.5 Environmental Regulations

Preservation operations are effected primarily by the Clean Air Act, and sometimes by the Clean Water Act. The Clean Air Act aims at reducing releases to the atmosphere. More recently, the Clean Air Act was amended to include National Emission Standards for Hazardous Air Pollutants (NESHAP), with specific requirements for Shipbuilding and Ship Repair Operations (10). The purpose ofNESHAP is to reduce emission of Volatile Organic Hazardous Air Pollutants (VOHAPs) through use, control, and reporting procedures, which ensure compliant marine coatings are used and the use of thinners is minimized. NESHAP regulations apply only to facilities considered to be a Major Affected Source (MAS) by virtue of the facility's Cleanp\ir permit. All painting operations at a MAS must comply with NESHAP regulations and the facility's NESHAP implementation plan. This could have the effect of restricting coatings and thinner usage. The shipbuilder should be queried as to their MAS status, and what restrictions, must be adhered to, if any.

23.3 IMPROVING THE PERFORMANCE OF PRESERVATION SYSTEMS

23.3.1 Critical Factors in Preservation System Performance

Though there are a multitude of factors, which determine the performance of a preservation system, three specific factors are predominant in the degree of success of a preservation system. They are: the proper selection of the type of preservation system, the service conditions in which the preservation system will be expected to perform, and the degree of surface cleanliness achieved prior to the use of the preservation system (11).

The selection of the type of preservation system used is based on several criteria. They include any known performance of the preservation system for similar applications, known chemical composition and physical properties of the preservation system, results of exposure tests of preservation systems under consideration, and anticipated environmental and service conditions.

The service conditions in which ships operate are severe from a corrosion and preservation perspective. The corrosive elements of nature are basically oxygen and water. These elements are typically abundant in the marine environment. Generally, little or no corrosion will occur unless both elements are readily available and in contact with the substrate. Other elements of nature are also damaging to the metals and preservation systems used onboard ship. They include salts, sunlight, particularly ultraviolet wavelengths which are especially damaging to topside coating systems; wind and wind-born particles and chemicals; biodegradation by fungi and bacteria; and alternate extremes of hot and cold which can occur during an extended construction period.

Experience indicates that the majority of coating failures qm be attributed at least in part to inadequate surface preparation (12). Factors which contribute include: improper customer supplied specifications, failure of the coating applicator to follow proper specifications, and inadequate inspection of the prepared surface to ensure that the surface preparation standard specified has been met.

23.3.2 Application Factors

23.3.2.1 Surface Preparation

Surface preparation is the most important factor in the performance of a coating (11). For this reason, it is extremely important that proper surface preparation be attained when coating a ship. Surface preparation includes inspection of the surface to be cleaned, inspection of fabrication defects of the substrate, pre-cleaning which may for example include a water wash, inspection for uncorrected fabrication defects, cleaning and inspection for cleaning defects (Figure 23.3) (13).

Mechanical surface preparation has been the traditional approach to preparing metal substrates prior to application of a coating system (12). Surface preparation methods vary from the most rudimentary hand scraper to laser beams. The broad spectrum of tools available suggests that surface preparation is a complex process and requires a good un-

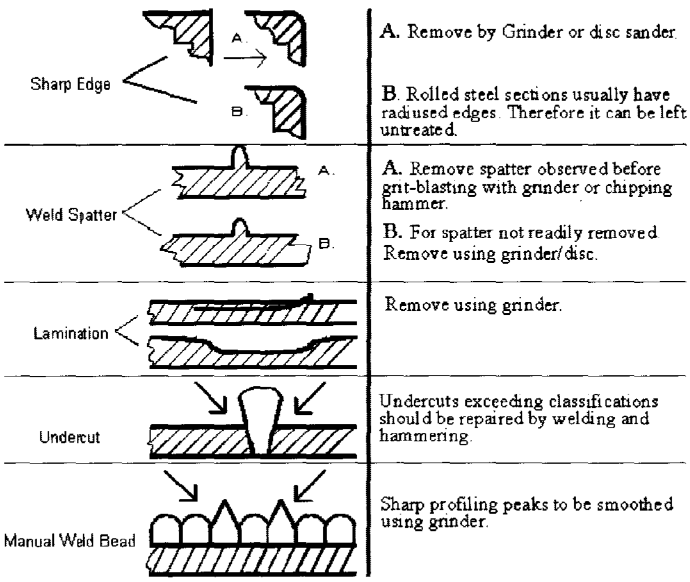

Figure 23.3 Preparation of Surface

derstanding of the mechanical surface preparation process and job parameters that dictate the selection of the process.

The selection of the surface preparation process is dependent upon many factors. They include job location, condition of the surface, required degree of cleanliness, profile, and environmental conditions. Job location is an important parameter. In the beginning of a ship's construction, the preferred method will likely be an automatic centrifugal abrasive wheel machine for in-shop production line work. However, if outside fabrication will be used, portable hand and power tools and manual abrasive blast machines will be used. If the job is located in an area where soluble salts could be a surface contaminant, then hydro blast cleaning (water-jetting) may be required.)

The condition of the surface also dictates which surface preparation method should be used. For the construction of ships, the structural plates are normally cleaned prior to the application of the primer coat by means of production line abrasive blasting equipment. The required degree of cleaning typically determines whether abrasive or hand/power tools will be used. If small areas of a surface need to be cleaned of Idose rust or other localized surface defects, then hand/power tools are usually used. However, if an entire surface needs to be cleaned to a defined degree of cleanliness, then blast cleaning is normally prescribed.

Many factors in surface preparation contribute and affect the service life of a coating system (11). They include:

- residues such as oil, grease, or soil which can weaken adhesion or the mechanical bond of the coating to the substrate, or various chemicals which can induce corrosion,
- rust on the surface,
- loose or broken mill scale which can cause early coating failure and tight mill scale which can cause later failure due to flaking,
- anchor tooth pattern (profile) which may be so rough that peaks cannot be protected by the millage of paint used or not rough enough causing coating failure due to loss of adhesion,
- sharp ridges, burrs, edges, comers, and cuts which prevent or reduce adequate coating coverage over peaks,
- surface condensation which if coated may result in blistering and delamination of the coating, and
- old coatings, which have poor adhesion to the substrate, are incompatible with the new coating systems, or too deteriorated to recoat.

The future pursuit of newer surface preparation methods depends largely on the regulatory authorities. Almost all the newer techniques are more costly and less productive than abrasive blasting. For situations in which air contamination (dust and lead paint particles) is a major problem, the use of some form of wet-blasting or hydro blasting technique appears to be the best choice at present.

23.3.2.2 Cleanliness requirements and standards

There are a number of standards for types and degrees of surface preparation, including those described by NACE International, formerly the National Association of Corrosion Engineers, the Society for Protective Coatings (SSPC), formerly the Steel Structures Painting Council, and the Swedish Standards Association (SSA). The NACE surface preparation standards cover four levels of abrasive blasting and one level for water-jetting. They are:

NACE 5 Water Jetting
NACE 4 Brush Off Blast Cleaning;
NACE 3 Commercial Blast Cleaning;
NACE 2 Near White Metal Blast Cleaning; and
NACE 1 White Metal Blast Cleaning.

These specifications are available from NACE International P.O. Box 218340 Houston, TX 77218-8340.

The SSPC surface preparation standards include several levels of cleanliness achieved by different methods. They are:

SSPC-SP 1 Solvent Cleaning;
SSPC-SP 2 Hand Tool Cleaning;
SSPC-SP 3 Power Tool Cleaning;
SSPC-SP 5 White Metal Cleaning.
SSPC-SP 6 Commercial Blast Cleaning;
SSPC-SP 7 Brush Off Blast Cleaning;
SSPC-SP 10 Near White Metal Cleaning;

SSPC-SP II Power Tool Cleaning to Bare Metal; and
SSPC-SP-12 Water Jetting

All the listed specifications are available from SSPC 4516 Henry Street Suite 301 Pittsburgh, PA 15213-2786.

The SSA surface preparation standards are:

Sa I Brush Off Blast Cleaning;
Sa 2 Commercial Blast Cleaning;
Sa 2YzNear White Blast Cleaning;
Sa 3 White Metal Blast Cleaning;
St 2 Thorough Power Tool Cleaning; and
St 3 Very Thorough Power Tool Cleaning.

Recent cooperative efforts by NACE International and SSPC have resulted in combining many of the NACE and SSPC standards, and as of the writing of this text, the following standards have dual NACE-SSPC titles:

SSPC-SP 5/NACE I
SSPC-SP 6/NACE 3
SSPC-SP 10/NACE 2
SSPC-SP 7/NACE 4
SSPC-SP 12/NACE 5

These standards are similar, but not identical, to the corresponding SSA standards.

The selection of which surface preparation level to achieve is dependent upon the expected service life requirements of the coating system, the coating system selected for use, and the cost of each surface preparation method. For example, if the section to be cleaned is part of the ship's inner bottom and tankage area, the surface cleanliness level of near white metal blast in accordance with NACE Grade 2 or SSPC-SP 10 or Sa 2-112 should be delineated in the specification. Or, if the purpose were to repair imperfections such as weld spatter, flux and 'ough welds, a more appropriate process would be to use a power tool.

23.3.2.3 Ambient environmental conditions

Environmental conditions are extremely important during the application of a protective coating system. Relative humidity, ambient temperature, and the substrate temperature are the most important parameters. Humidity can affect the corrosion of prepared but not yet painted steel as well as the cure of applied coatings. Humidity is necessary for atmospheric corrosion. A thin layer of condensed water deposits on the surface to provide the electrolyte needed for electrochemical corrosion. Although necessary, humidity alone is not sufficient. Even in very humid environments, corrosion of uncontaminated surfaces is often relatively low in non-marine and unpolluted atmospheres. Pollutants, salts, and other atmospheric contaminants increase atmospheric corrosion by enhancing the electrolytic properties and stability of water particles that condense from the atmosphere. A combination of high humidity, high average temperature, and the presence of industrial pollutants or air-entrained sea salt increase atmospheric corrosion rates. Vernon (14) was the first to discover that a critical relative humidity exists below which corrosion is negligible (15). Typical corrosion behavior of iron as a function of relative humidity of the atmosphere has been shown. Heating the air or better still, reducing the moisture content can serve to reduce relative humidity. Lowering the relative humidity to 50% suffices in many cases. If the presence of unusually hygroscopic dust or other surface impurities is suspected, the value should be reduced still further. Humidity levels also affect the cure of most coatings. Humidity should generally be maintained below 85% during the cure of epoxy coatings and below 50% for some extended performance epoxies, whereas inorganic zinc silicate coatings require a minimal level of atmospheric moisture for proper cure.

23.3.3 Design Factors

Designers must consider the total ship structure. Coatings can seldom, if ever, correct the effects of poor design. *Preventive* control, beginning with design, offers the best answer to the difficult problem of corrosion as stated in Section 23.2.

23.3.3.1 Geometry

The geometry of a structure is extremely important in determining the service life of the component and the preservation system used. The effects of geometry directly influences corrosion tn three primary ways. They are time of wetness, environment, and drainage (16). The time of wetness can be increased by the presence of features that trap and hold liquids by contact with absorbent materials, or by features, which inhibit drying of the surfaces after they are wet. Geometry can affect the environment, which is present on the metal surface or can produce a different environment between various sites on the metal. Complete drainage is as important in structures as it is in fluid handling and storage systems. Crevices are the primary cause for trapped liquids and they are frequently the result of designs, which lead to poor drainage. When crevices cannot be eliminated, the risk of corrosion in the crevice area must be minimized by careful matching of the materials to the service environment, by preventing ingress of corrodent into the crevice, or by other means of preventing crevice attack, such as a change in the environment or the application of cathodic protection.

Geometry parameters, which reduce the propensity for corrosion, include (12,16):

- simple shapes are usually less susceptible to corrosion than more complex shapes and are usually less affected if corrosion does occur (Figure 23.4),
- corrosion prone areas must be made accessible for in-service maintenance and repair,
- prevent trapping liquids and absorbent solids within the structural assembly (Figure 23.5),
- design the geometry of structures to prevent condensation and accumulation of corrosive media in joints and other spaces,
- avoid laps and crevices in structural design. If unavoidable, the laps must face down on exposed surfaces and such connections must be well sealed (Figure 23.6),
- do not use back-to-back angles that are bolted or intermittently welded, and
- minimize horizontal runs of welding especially if those are not accessible for cleaning, grinding, or blasting. If possible, design in a slight angle to horizontal runs to allow for drainage.

23.3.3.2 Material compatibility

Among the most fundamental design activities, the appreciation and evaluation, of materials of construction take the lead. The designer must be concerned about compatibility. All inter-material properties must be properly appreciated and evaluated before any final design decision is taken. This evaluation must take into account problems caused by direct contact between dissimilar metals or induced by changes of polarity, by transport of electrons through a medium, by transport of metallic particles in the environment, by stray electrical currents, or by any other adverse effect, arising from the proximity of incompatible materials.)

Considerations for material compatibility includes (12):

- faying surfaces of dissimilar materials should be designed for effective separation. Separation of materials of suitable shape, thickness, consistency, and mode of application should be used such as, gaskets, butyl tape, and sealant,
- insulation must be sufficiently thick and cover sufficient areas ofbi-metallic joints to prevent conductive medium, usually condensation, from by-passing the insulation and reaching the faying surface of the connection,
- contact between structural metals and plastics can create very tight crevices, which have a propensity for corrosion (crevice and chemical attack). Test for compatibility,
- large cathodic areas of metals with small anodic areas must be prevented in design of structures exposed to corrosive environments,

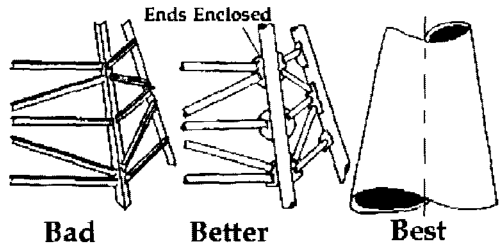

Figure 23.4 Simple Shapes Are Less Susceptible to Corrosion

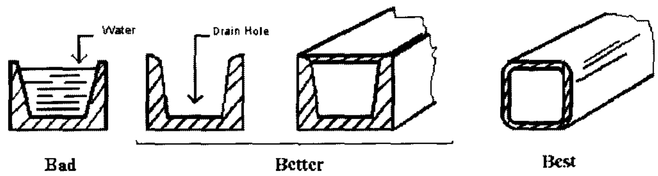

Figure 23.5 Prevent Entrapment of Liquids

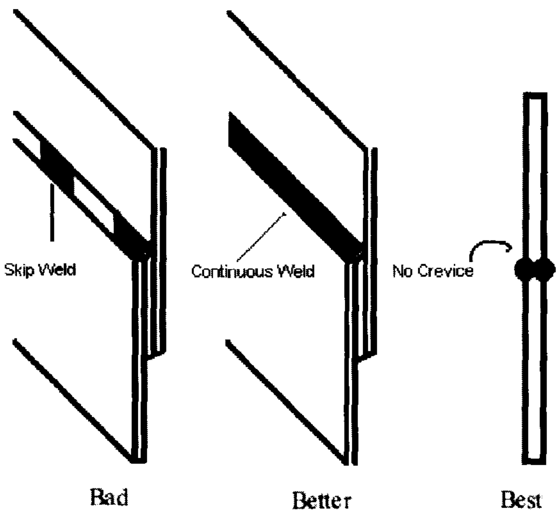

Figure 23.6 Eliminate Crevices

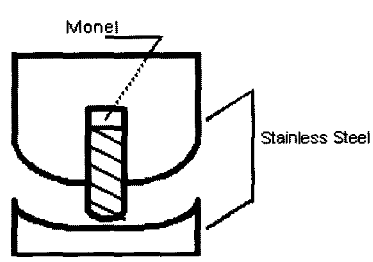

Figure 23.7 Key Structural Unit Made of More Corrosion Resistant Material

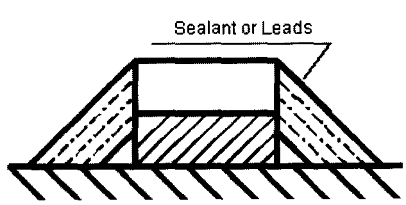

Figure 23.8 Protect Edges of Clad Metals

- key structural units, especially if smaller in size than adjoining units, should be made of more corrosion resistant metals provided mechanical requirements allow (Figure 23.7),
- less corrosion resistant structural members in bi-metallic structures should be larger or be of thicker metal form to allow for corrosion waste and sacrificial protection of cathodic members,
- design for easy replacement of anodic structural members,
- design to conduct moisture away from bi-metallic joints,
- edges of clad metals in corrosive environments must be well protected (see Figure 23.8),
- select materials for their functional suitability and ability to maintain their functional safely for an economical period of time at a reasonable cost,
- specify accurately and test on delivery for conformance to specifications,
- select more corrosion resistant materials for critical structural members or where relatively high fabrication costs are involved,
- compromise where necessary-trade-off mechanical advantage for corrosion protection,
- ·do not mix long and short life materials in sub-assemblies that cannot be repaired, and
- do not use materials producing corrosive or toxic fumes for steel structures, which are subject to fire hazard.

23.3.3.3 Stresses, vibration, and fabrication

Many manufacturing processes can, if improperly performed, affect the properties of a material as much or more than its composition. Hot work such as welding and cold working such as bending, both induce residual stresses. Some stresses are caused, not by deficiencies in the flaterials used, but by the improper use of fabrication practices. During the fit-up process of ship construction, stresses can be induced by either the poor fit of components, which are then drawn into conformance with attendant residual stress or through the thermal effects of joining by welding.

If unprotected corrosion can result from the resulting cathodic action between the changed material and the base material.

Vibration can induce corrosion in two principle ways, fretting corrosion and vibration-induced fatigue. The avoidance of excessive vibration is good practice from both a mechanical and a corrosion perspective. Fretting corrosion occurs when there is relative motion at the interface between two surfaces. This relative motion can either cause accelerated corrosion through the removal of protective films or through direct abrasion effects. Fretting can also remove protective coatings, such as paints or plating.

23.3.4 Quality Assurance and Quality Control

The importance of quality assurance (QA) and quality control (QC) is without question (see Chapters 4 and 5 for additional discussions on QA). However, it must be recognized that any inspection, even the most casual kind, is an expense for the shipbuilder and ship owner. Even during the performance of work, fundamental inspection requires time. Inspection, in its simplest form, occurs when the worker stops after a certain portion of the work is completed, and examines the completed work for adequacy. Formal inspections are significantly more costly. Inspection procedures must be written, and the quality of work witnessed and documented on a periodic basis. The inspector must have access to the work area, and be allowed sufficient time to complete the inspection. Often the inspection process is performed at the expense of production. Although other tasks can be performed during the inspection, the net result is that the more stringent the inspection requirements, the longer it will take to complete the task. Inspections are an insurance against the possibility of a highly expensive premature failure of the task at hand. There are a multitude of QA and QC requirements for the construction of vessels. However, the largest number of inspections during the construction of vessels is associated with the preparation of the substrate and application of the coating system (12).

23.3.5 Fabrication Practices and Production Sequencing

Without a doubt, the optimal time for the application of coating systems and other corrosion prevention measures is during construction. All areas of the vessel are more accessible. Also, during construction, conditions are more suitable for superior surface preparation and coating than at any other time during the ship's service life. When a ship is being constructed, areas to be preserved are usually assembled and sufficient time is allocated for the preparation and application of the preservation system, normally a coating. When coating systems are selected, the overall cost effectiveness should be studied, including the cost of maintenance, repair, and out of service costs. Surface preparation and coating application are traditionally scheduled last and the least considered operation of ship construction (12). Coating during the modular stage of construction has partially relieved some of the problems associated with a hastily applied coating system. However, preservation of areas marked or damaged during erection of blocks and final coating is still dependent on the work schedules and completion of other crafts. Therefore, efficient planning and operation must be maintained if costs are to be limited and controlled. Coatings are the primary method used to protect surfaces. The type of coating applied, surface preparation and film thickness will to a degree, depend on expected service conditions, such a salt-water immersion, fouling, and atmospheric exposure.

The underwater hull area of a ship can be one of the most critical areas for protection. Because it is observed only when the vessel is in dry dock or through periodic diver inspections, coating systems and other methods of corrosion control such as cathodic protection, become increasingly important. Hull roughness caused by corrosion adversely impacts on ship's speed, fuel consumption, endurance, and operational costs.

23.3.6 Training

In the coatings industry, the use of high performance coatings, the critical need for effective surface preparation and paint application, and the continued development of sophisticated equipment make it necessary to have ongoing training programs for workers.

Training programs make good economic sense. It is simply too costly for most companies to have their employees learn by trial and error. Anticipated higher prices for raw materials will increase the cost of the paint, which makes it increasingly expensive to waste materials. Training can also be used to target and eliminate specific or recurring problems.

For training to be effective, training must be accepted throughout the company. Management must understand the need and objectives oftraining and support it. Once the employees have been trained, they must be allowed to practice to obtain the greatest benefit.

The training needs to be focused on the problems faced by the company. To determine the specific training needs, four approaches are recommended. They include perfolnance reviews, records, patterned interviews, and surveys. Once needs are identified, a logical step is to determine whether training can solve the problems, or whether procedural changes would be more effective. Training objectives should be outlined. Up and down the company's organization, all employees can benefit from training, but only if the training program is designed to meet the specific needs identified. It cannot be over emphasized that the causes of problems and not their symptoms must be carefully determined and analyzed before training objectives are set and a determination is made on which employees will benefit most from a training program.

Training should be compatible with the way adults learn. Suggested guidelines include (12):

- adults must want to learn,
- adults learn only if they feel a need and can see the immediate benefits, such as learning a technique that makes their job easier,
- learning and retention rates increase with active involvement by the student which includes immediate practice and continued use of the skills learned,
- adults build new learning on their previously acquired knowledge and experience,
- informal learning environment, and
- increased retention if information is presented in several ways, which includes making a strong impression on the five, senses, especially seeing and hearing. Lectures, visual aids and group discussions have proven to be effective teaching methods.

Once a training program has been implemented, the effectiveness of the program must be assessed in terms of time and expense. One evaluation method is to measure the job results. Did the program address the specific areas identified by the company? Have costs decreased and production and/or quality increased? Are rework requirements decreasing? Concurrent with the tangible benefits of a successful training program, other qualitative benefits may arise. These include improved morale, a greater sense ofloyalty to the company, and decreased organizational tensions.

23.4 COST-BENEFITANALYSIS

Since the purpose of protective coatings is primarily economic, no practical treatise on protecting the structure is complete without a discussion of comparative costs. Access to basic information and procedures identifying candidate systems that are suitable in the specific environment, costing each, making a.selection, and then justifying the choice is essential.

One methodology is to use paint and coatings as basic expense items without salvage value or depreciation considerations (17). They are, however, tax deductible, in most instances. Only a few calculations are needed to compare one system with another and measure each system's true cost in comparable dollars. In most cases, cost comparisons are performed based on the service life costs of each system to one another. For each system used or considered, simply list the timing, number, and cost of painting operations required to protect the structure for its projected life. This should include such items as original painting, touch-up, touch-up and full coats, and full repainting. The cost of each painting operation should be calculated in three categories: at current cost levels; at net future value (NFV) levels-the current cost with inflation included; and at net present value (NPV) levels- the present worth of the inflated cost (NFV) in monies today invested at current interest rates. For a detailed presentation on the application of these economic factors, see Chapter 6 - Engineering Economics.

By making these calculations for each of the system's painting operations, the true cost and number of painting operations can be compared and the coating selection based on a comparable cost basis. A system may be cheaper to install initially, but if it has a shorter life and requires frequent repainting, its life cycle cost will be greater because of the more frequent repainting, and the impact due to paint disruptions.

23.5 RECOMMENDATIONS FOR DESIGN AND NEW CONSTRUCTION

Engineered structures should be designed so as to provide the desired functional qualities for the required period of service. Therefore, a structure should not be over or under designed. Thoughtful design requires more than the provision of adequate strength. The part must also last for a given period of time. But, designing for too long a life may constitute over design if it involves the use of higher cost materials or costs more.

Crevice corrosion produces the greatest number of failures of equipment due to poor design, which produce concentration cell action (6). Examples include gasketed flanges, rolled joints between tubes and tube sheets in heat exchangers, and faying surfaces between tanks and supporting structures. The two major design deficiencies causing such attack are the presence of crevices and pockets, which retain deposits on a metal surface. Moisture and chemical solutions may be trapped within crevices and become stagnant. These chemical differences in enviroIlPlent cause potential differences essentially similar to thore encountered in galvanic corrosion. Much has been written on the subject and sketches of proper design configurations have been available. Some of the more common recommendations, which continue to be germane, are illustrated in Figures 23.9,23.10, and 23.11 (12,16).

The galvanic series (Figure 23.2) can be very useful to the designer, even though the positions of the metals in the galvanic series can change somewhat with varying environmental conditions and temperature. The designer should always consider the relative areas of the cathode and the anode before selecting dissimilar metals. A rule of thumb that may be used in designing for dissimilar metals is called the Area Ratio Rule (18), which states that the rate of corrosion will vary with an increase or decrease in the area ratio of the more noble metal to the less noble metal when connected together in an electrolyte.

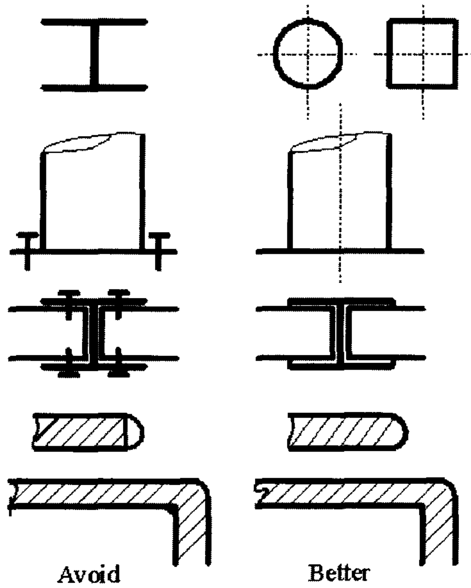

Figure 23.9 Proper Design Configurations

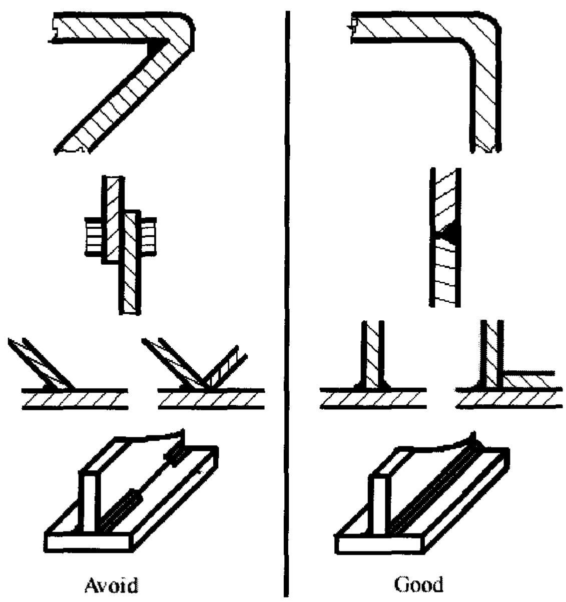

Figure 23.10 Proper Design Configurations

For example, if the anode is one-half the area of the cathode, the corrosion rate will be doubled compared with the corrosion rate when both areas are the same. Conversely, if the area of the anode is double that of the cathode, the corrosion rate will be half. The area rule only applies when the cathode controls the corrosion reaction. Since there are differences in the various galvanic series, the safe procedure for the designer is to specify that the anode and cathode be totally electrically insulated from each other.

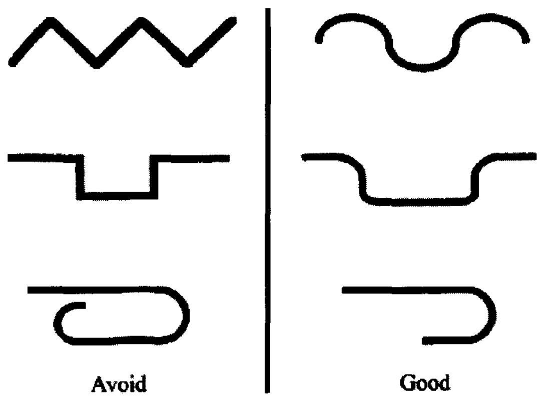

Figure 23.11 Proper Design Configuration

There are however many environments or designs in which insulation is not feasible, such as high temperature or aggressive solutions where the insulation will deteriorate. In these cases, the more noble metal should be used for joining or fastening the less resistant metal. There have been many applications of dissimilar couples where excellent service life has been realized, even though a study of the galvanic series chart would indicate that such couples might fail. The reason for the success was that the designer followed the Area Ratio Rule and made the anodic side of the couple much larger in area than the cathodic side of the couple. Practical examples are stainless steel bolting on aluminum alloy equipment and Monel bolts used to hold together parts of steel condensers exposed to brackish cooling water.

Protective coatings on joints can be specified to insulate couples from each other, but this can sometimes be a rather dangerous procedure. For example, the less noble (anodic) materials should not be painted without also coating the more noble materials. Painting the anodic material witll>ut painting the cathodic material would, ideally reduce the anodic area to zero, while the cathodic remains large. However, any coating failure or coating holiday in the anodic area results in a very large adverse area affect and becomes a concentrated area for current flow and subsequently the corrosion will be concentrated in this small area.

What can the ship designer do to prevent galvanic corrosion in their design? Recommendations include (18):

- review designs to assure no galvanic couples have been inadvertently included,
- use galvanic series tables to select suitable couples,
- when possible, electrically separate the dissimilar metals with an electrical insulator;
- when insulation is not practicable, follow the Area Ratio Rule and specify that the area of the anode be much larger than the area of the cathode, and
- when specifying that paint be used to insulate one member of a couple from the other, never specify painting of the anode only. Either paint, both the anode and the cathode or just the cathode.

When designing for protective coatings, it is essential that the surface to be coated be prepared properly to accept the protective coating. Otherwise, the protective coating will not achieve the intended service life. To assure that the design of the ship structure is amenable to the coating system, the following design recommendations should be taken (12,16,18):

- eliminate sharp comer and edges,
- use butt welds instead of lap welds-lap welds are potential sources for crevice corrosion,
- remove weld spatter,
- provide drainage in recessed zones,
- specify the removal of rough surfaces by sanding, grinding, or other means,
- specify that welds be continuous with no intermittent welding,
- specify the rounding of all comers and edges,
- eliminate difficult to reach places-consider life cycle maintenance of the compartment,
- specify surfaces be easily accessible;
- provide a continuous and even surface to allow complete bonding of the coating to the metal surface,
- when a thick plate is to be joined by a thinner plate, design the surface to be coated to be flat,
- relocate if possible internal stiffeners or structural supports for tanks on the outside of the tank, leaving the inside surface smooth. If the stiffeners must be located inside the tank, the coating will be correspondingly more difficult to apply,
- do not incorporate crevices or pockets in the design. Where crevices cannot be avoided, specify that they be welded and welds be ground prior to the application of the coating system,
- remove mill scale from the steel surface. Mill scale is cathodic to steel and may spall, thereby taking the coating system with it, and
- provide easy access for tanks, vessels or piping for coating application and inspection (Figure 23.12).

The design of a structure is frequently as important as the choice of materials of construction. A design should consider mechanical and strength requirements together with an allowance for corrosion. In all cases, the mechanical design of a component should be based on the material of construction. In other words, *design corrosion out* of the system instead of waiting until the equipment fails in service.

This is enhanced by close communications between designers and corrosion engineers and all major projects including funds for utilization of corrosion engineers. Fontana (3) believes corrosion engineers should also sign off on equipment drawings, not only the design engineers. Some design rules that should be followed are (3,16):

- weld rather than rivet tanks and other containers. Riveted joints provide sites for crevice corrosion as discussed in Section 23.3.3,
- design tanks and other containers for easy draining and easy cleaning. Tank bottoms should be sloped toward drain holes so that liquids cannot collect after the tank is emptied (Figure 23.13),
- design systems for easy replacement of components that are expected to fail rapidly in service. Frequently, pumps in chemical plants are designed so that they can be readily removed from a piping system,
- avoid excessive mechanical stresses and stress concentrations in components exposed to corrosive mediums. Mechanical or residual stresses are one of the requirements for stress corrosion cracking as discussed in Section 23.3.3. (This recommendation should be followed especially when using materials susceptible to stress corrosion cracking),
- avoid electrical contact between dissimilar metals to prevent galvanic corrosion as described in Section 23.2.1. If possible, use similar materials throughout the entire structure, or insulate different materials from one another,
- avoid sharp bends in piping systems when high velocities and/or solids in suspension are involved,
- provide thicker structures to take care of impingement effects,
- ensure materials are properly selected;
- list complete specifications for all materials of construction and provide instructions to ensure specifications are followed all the way through to final inspection,
- be sure relevant codes and standards are met,
- set realistic and scheduled dates for delivery of equipment,
- specify procedures for testing and storage of parts and equipment. For example, after hydraulic testing do not let the equipment sit full or partially full of water for any extended period of time. This could result in microbial corrosion, pitting, and stress corrosion,
- specify operating and maintenance procedures,
- design to exclude air. Oxygen reduction is one of the most common cathodic reactions during corrosion, and if oxygen is eliminated, corrosion can often be reduced or prevented, and

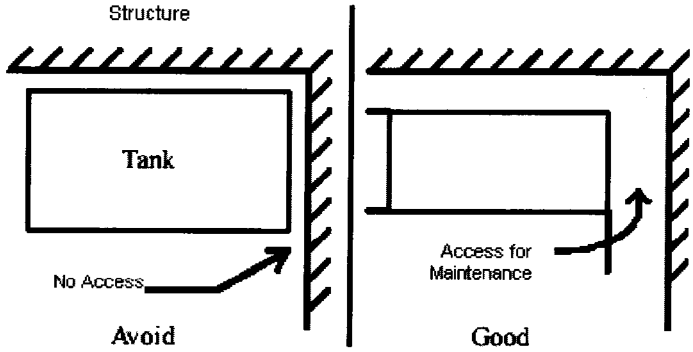

Figure 23.12 Design in Easy Access

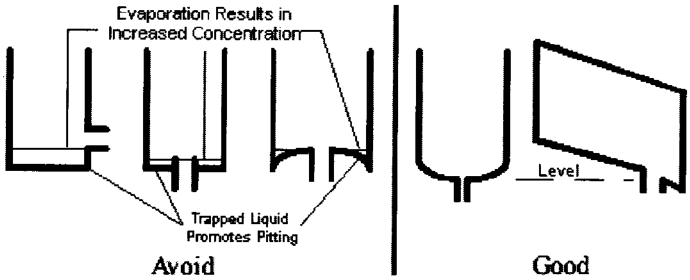

Figure 23.13 Design for Easy Drainage

- avoid heterogeneity. Dissimilar metals, vapor spaces, uneven heat and stress distribution and other differences between points in the system lead to corrosion damage. Hence, attempt to make all conditions as uniform as possible throughout the entire system.

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Chapter 24

Machinery Considerations

Alan L. Rowen

24.1 NOMENCLATURE

ADGT	aircraft-derivative gas turbine
bkW	brake power, in kilowatts
bSFC	brake-specific fuel consumption
DFM	distillate fuel, marine
HDGT	heavy-duty gas turbine
HFO	heavy fuel oil
HVAC	heating, ventilation, and air conditioning
LNG	liquefied natural gas
MCR	maximum continuous rating
MEP	mean effective pressure
MGO	marine gas oil, a light distillate fuel
No. 2-D	diesel fuel, a light distillate fuel
NOx	oxides of nitrogen
RCGT	regenerative-cycle gas turbine
rpm	revolutions per minute
SCGT	simple-cycle gas turbine
SFC	specific fuel consumption
skW	shaft power, in kilowatts
SSDG	ship's service diesel generator
TG	turbo generator

24.2 GENERAL CONSIDERATIONS

24.2.1 Introduction

The power plant of a ship generally provides for both its propulsion and for ship's services, which include steering gear, deck machinery, navigation and communication equipment, the hotel load, and support of cargo, trade, or mission requirements. This chapter will be confined to the machinery in the power plants of modem merchant ships. For further discussion of ship machinery see references 1 through 3. The power plants in common use today in merchant ships are those based on diesel engines and steam turbines. Gas turbines are only infrequently used in merchant ships, but are likely to become more common in the near future, and are included here. Nuclear power plants are used in many submarines, in a limited number of large warships, and in a class of Russian Arctic icebreakers, but are not generally considered viable for merchant ships, and will not be discussed in this chapter. Gasoline engines are widely used in small boats and in pleasure craft, but are rare in other marine applications, and also will be excluded from this chapter.

24.2.2 Descriptions of Power Plants

Typical machinery arrangements are listed in Table 24.1 and shown in Figures. 24.1 to 24.3.

24.2.2.1 Diesel plants

Diesel propulsion predominates for merchant ships of all types and sizes today. Diesel engines divide into groups as low-speed, medium-speed, and high-speed engines.

Low-speed engines are very large. They are specifically designed for ship propulsion, with crankshaft rpm low enough to enable direct drive of the propeller. There is therefore one engine per propeller, mounted on the tank top, in line with the propeller shaft, and centrally located for a single-screw ship. Unless a controllable-pitch propeller is fitted, the engine must be direct reversing. Low-speed engines have from

TABLE 24.I Merchant Ship Power Plants

	Oil-Fired Steam Turbine	*Coal-Fired Steam Turbine*	*Low-Speed Diesel*	*Medium-Speed Diesel*	*High-Speed Diesel*	*Aircraft-Derivative Gas Turbine*	*Heavy-Duty, Simple-Cycle Gas Turbine*
Power Range, Kw	up to 60 000 per unit	up to 60 000 per unit	3000 to 100 000 per engine	1000 to 25 000 per engine	up to 4000 per engine	up to 50 000 per turbine	up to 40 000 per turbine
Typical Ships	LNG ships; older ships of all types	some ore and coal-carriers	most merchant ships	merchant ships; naval auxiliaries	smaller ships of all types	warships; fast ferries	some fast ferries
Current Status	unlikely for new ships	feasible	most common for merchant ships	increasing use in merchant ships	dominates in smaller ships	dominates in warships	increasing use in fast ferries
Acquisition Cost	high	higher than oil-fired steam	highest	fairly high	lowest in power range	lowest at high power	high
Minimum Fuel Quality	residual	coal	heavy blend	intermediate blends	light distillate	light distillate	selected light blends
Fuel Consumption	high	high	lowest	lowest	low	high	high
Maintenance on Minimum Quality Fuel	least	high	low	high	low	low at sea, but high overall	moderate
Mass and Volume	moderate	moderate	high	moderate	low	lowest	low

four to twelve cylinders arranged in-line, with power output ranging from less than 3000 kW to over 60 000 kW.

Medium-speed and high-speed engines are more compact than the low-speed engines, but must drive the propeller through gearing or by electric drive. These engines have four to ten cylinders in-line, or as many as 24 cylinders in a V-configuration. The rated power output of medium-speed engines ranges from under 1000 kW to more than 20000 kW. High-speed engines cover the power range from less than 100 kW to over 3000 kW. In fact, there is no clear difference between smaller, higher rpm, medium-speed engines, and the larger, lower rpm, high-speed engines, with the distinction mostly in the perceptions of the designers and users. Medium- and high-speed engines are often combined in pairs, side-by-side, geared to a single prfpeller shaft. Some medium-speed engines can be directly reversed. For other engines reversing is provided by the gear set, by a controllable-pitch propeller, or by electric drive. With diesel-electric drive, the output of several diesel-generator sets can be combined.

In all but the smallest diesel plants two, or more commonly three or more, independent diesel-generator sets are fitted. An attached generator, driven directly by the main engine, may be fitted as well. A waste-heat boiler, recovering heat from the engine exhaust, is common. With low-speed engines and the larger medium-speed engines the auxiliaries are independently driven by electric motors, but the smaller the engine, the more common are attached auxiliaries.

24.2.2.2 Steam plants

Steam plants are completely dominant among liquid natural gas carriers in current service, and coal-fueled ships are necessarily steamships. In addition, many older, oil-fired steamships remain in service, some of which have been extensively modernized.

The typical steam plant, of which Figure 24.3 is an example, has two boilers side-by-side, supplying steam to a cross-compound propulsion turbine comprised of separate high-pressure and low-pressure turbines, the power outputs of which are combined at the reduction gear to drive the propeller. Astern running is achieved by admitting steam to separate astern stages within the casing of the low-pressure turbine. Steam is also supplied to one or more independent turbo generators, as well as to the turbo-feed pumps, but most other auxiliaries are driven by electric motors. Exhaust steam is condensed using large quantities of seawater, and returned to the boiler .via a series of feed-water heaters. Some plants use scoop-circulation of the condenser when the ship is moving ahead at speed, which requires carefully designed ducts to be integrated into the hull structure, usually with a lip at the overboard discharge to induce the flow. On tankers, cargo pumps are generally driven by steam turbines, and large quantities of steam may be used at sea for cargo heating. Standby diesel generators are common. Plants with single boilers, single-casing turbines, attached auxiliaries, or turbo-electric drive are all practical but not typical.

24.2.2.3 Gas turbine plants

Gas turbines can be divided between aircraft-derivative units (ADGTs) and heavy-duty gas turbines (HDGTs), originally designed for stationary power production, and can be further divided between simple-cycle units (SCGTs) and Ie-generative-, or recuperative-cycle units (RCGTs). **Few of** the merchant ships built a generation ago with gas **twbUE**

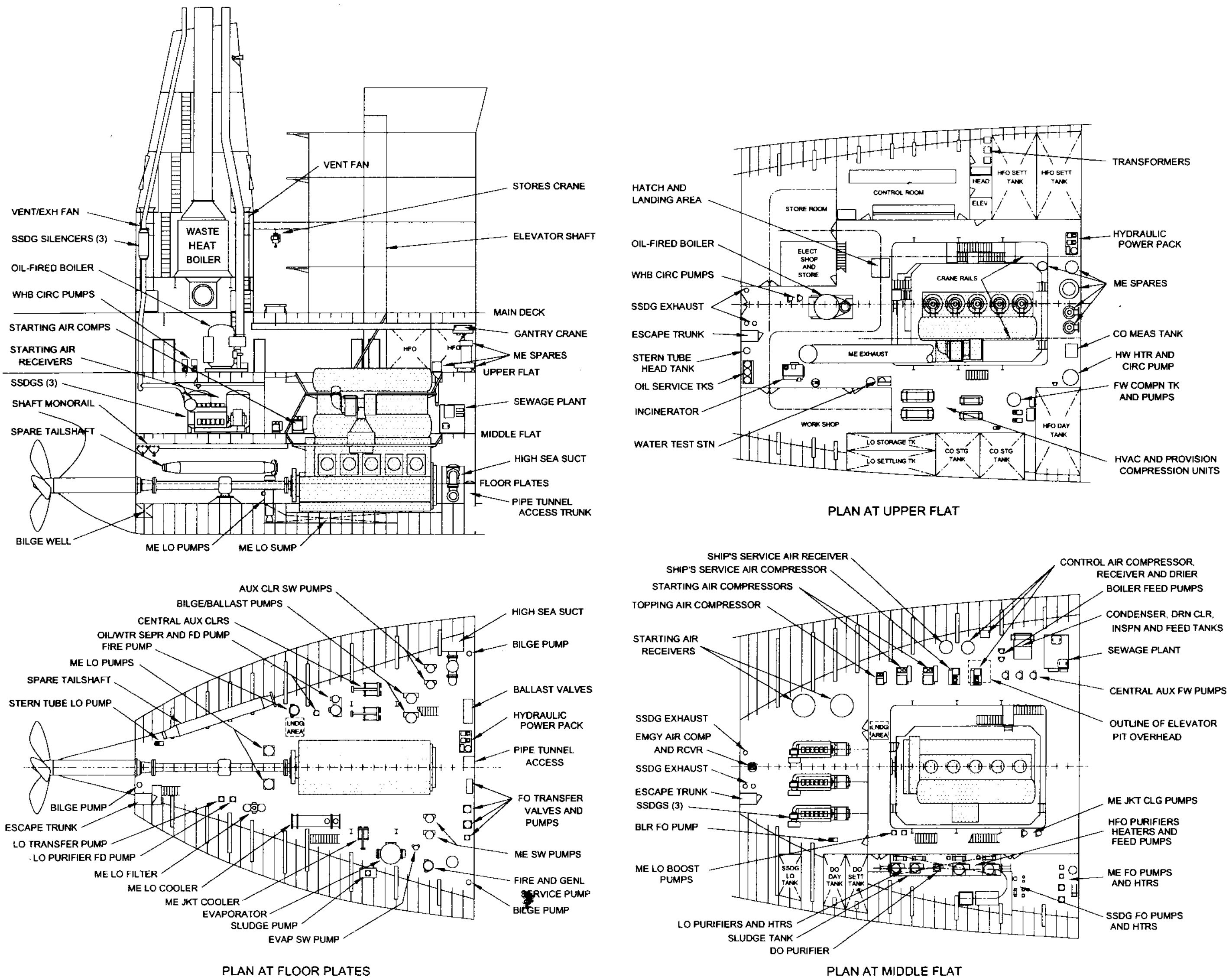

Figure 24.1 Low-speed Diesel Machinery Arrangement

propulsion remain in service with their original machinery, but simple-cycle, aircraft-derivative gas turbines have become the prime movers of choice for a wide range of naval vessels (4). In most of these naval vessels, it is the high power density of simple-cycle gas turbines, which is their principal advantage, which has driven the selection. Newer merchant-ship applications have tended to be those where high power density is useful, as in high-speed ferries. This fact favors the simple-cycle gas turbine over the regenerative-cycle gas turbine, although an advanced-cycle machine now under development, which uses an intercooled compressor and a compact regenerator, may redress this issue.

Marine gas turbines of 40000 kW and more are available, but only at the discrete power levels at which they are manufactured. The larger gas turbines are usually supplied and installed in an acoustic enclosure of approximately container dimensions. In most applications they are geared to the propeller, but electric drive is also feasible. Two units may be fitted side-by-side, geared together to drive a single propeller shaft. Astern power must be provided by the gear set, by a controllable-pitch propeller, or by electric drive.

Advantages of gas turbines over other prime movers are:

- high power density and low specific weight, especially for ADGTs;
- manufacture as standardized units, with a broad base of experience in other applications;
- little requirement for on-board maintenance;
- rapid start and assumption of load; and
- low exhaust emissions, especially of NOx.

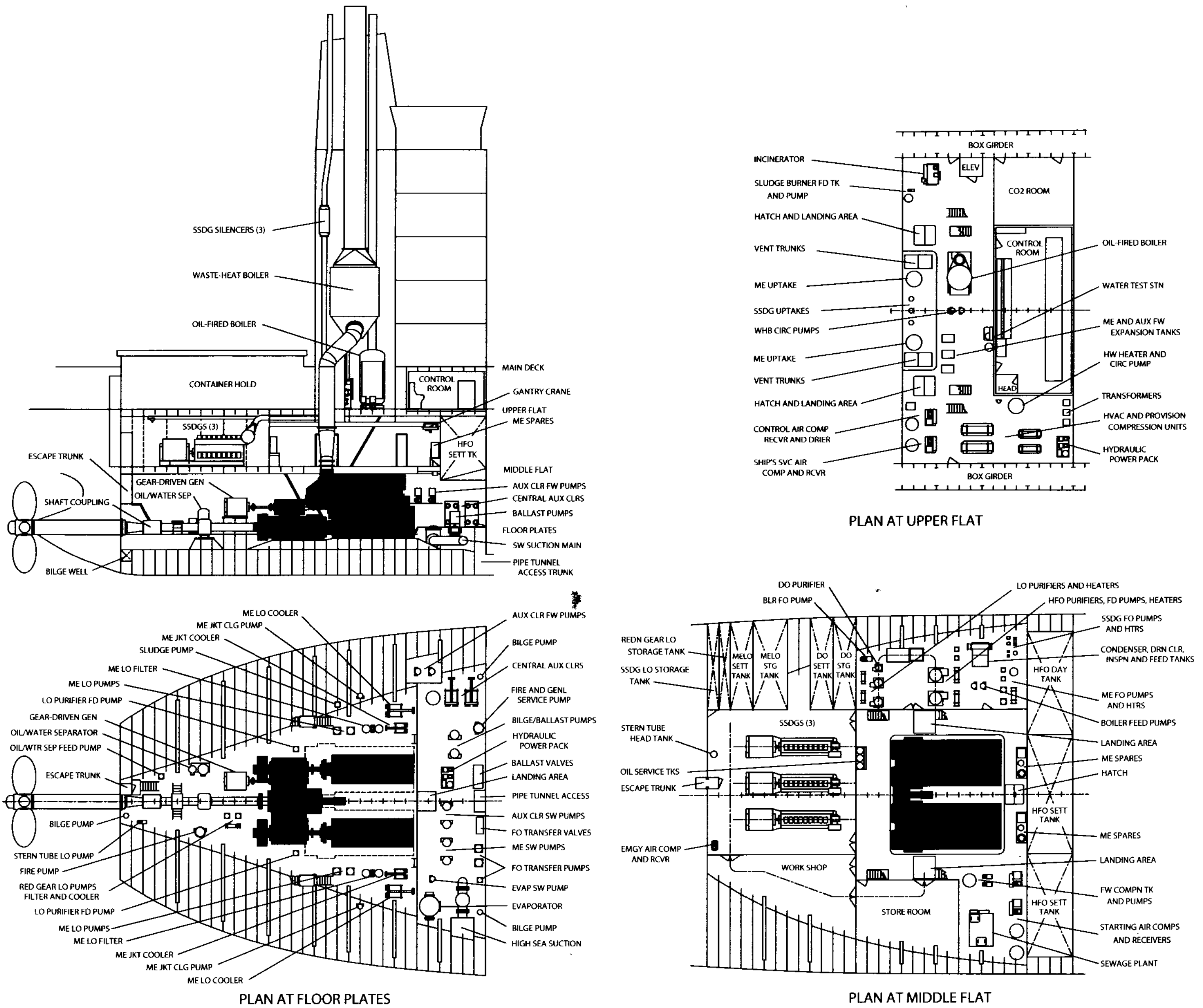

Figure 24.2 Medium-speed Geared Diesel Machinery Arrangement

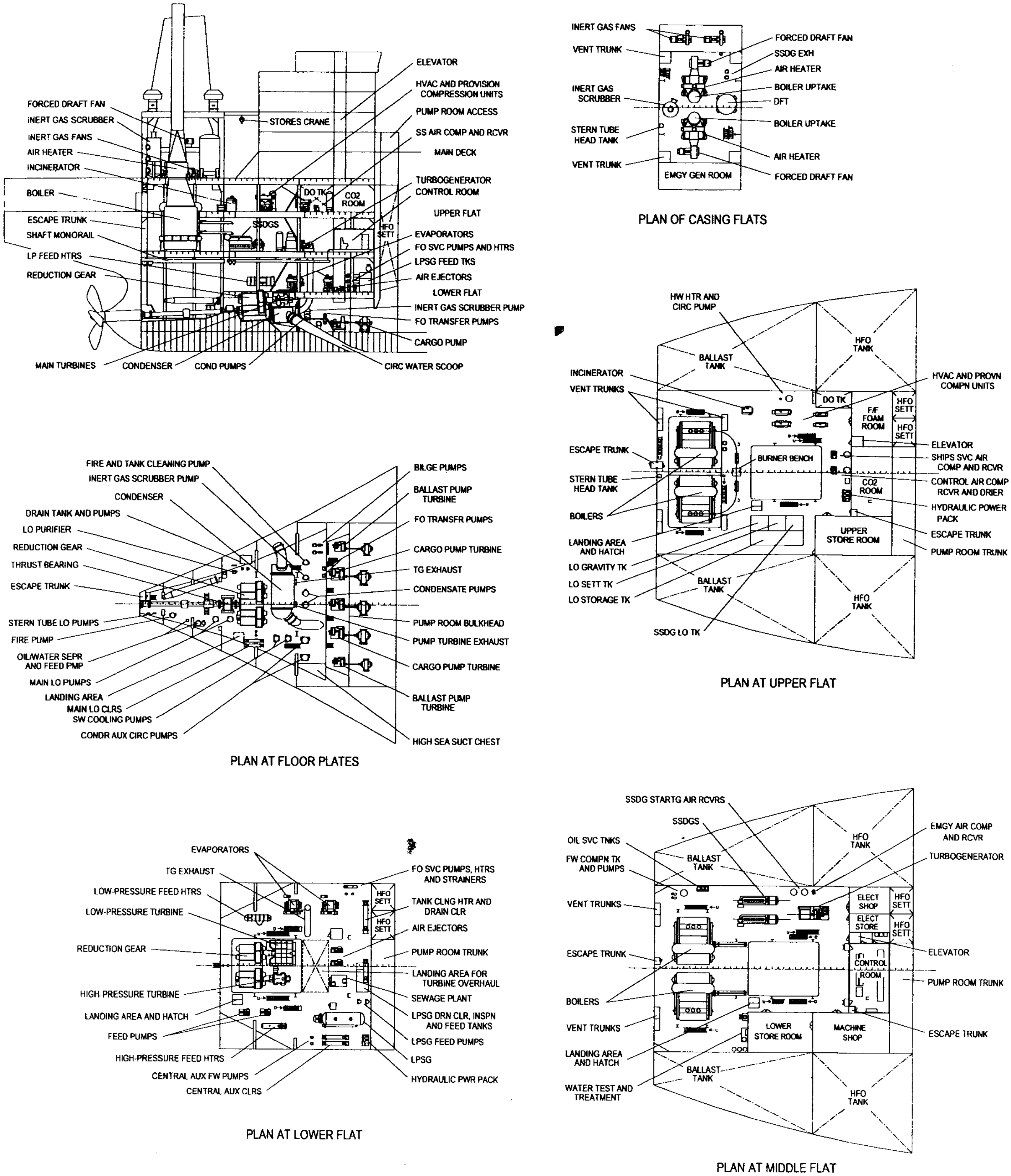

Figure 24.3 Steam Plant Machinery Arrangement

Disadvantages are:

- sensitivity to fuel quality;
- high fuel consumption, especially at less than full power;
- high air and exhaust flows;
- sensitivity to losses in air and exhaust ducts;
- reduced performance at high ambient-air temperatures;
- high maintenance cost, especially for ADGTs;
- no inherent or simple reversing capability; and
- output at high rpm, which requires speed-reducing transmissions for propeller drive.

The combustion air must be drawn from the weather, so the plants are characterized by very large intake and exhaust ducts. Attached generators, driven from the reduction gear, may be fitted. Independent generators may be driven by gas turbines or diesel engines. Waste-heat boilers are feasible, but because they add to the volume, weight, and complexity, they are not common. Most auxiliaries are independently driven by electric motors.

24.2.3 Machinery Arrangements

Several examples of machinery arrangements are shown in Figures 24.1 to 24.3. Regardless of machinery type, the equipment in a properly designed plant is arranged to allow for such factors as the following:

- safety considerations, including fire hazards;
- requirements for suction, gravity flow, static head, air intake, and mechanical connection;
- access for operation, inspection, maintenance, repair, overhaul, and renewal;
- ship's structure;
- simplicity of construction;
- noise and vibration.

These factors are discussed below, and their effects are evident in the illustrated arrangements.

When the machinery space is located aft, the after-most position of the propulsion machinery is determined by the hull form, by the width of the machinery, and, usually, by the need to withdraw the tail shaft inboard. Inboard withdrawal of the tail shaft is normal with fixed-pitch propellers; outboard withdrawal is normal with controllable-pitch propellers and can be arranged in any case, although it may require the removal of both the rudder and propeller.

Pump suction criteria affect most machinery systems, usually forcing fuel-transfer pumps, lubricating-oil circulating pumps, seawater cooling pumps, bilge pumps, ballast pumps, and fire pumps to be located on the lowest level. Other pumps, including boiler-feed pumps and fuel-service pumps, may be located on intermediate flats, but only when their sources of suction are also elevated. Many tank locations are therefore related to pump locations, and are also subject to considerations that may include gravity filling or drainage, venting, or static-head requirements.

Most machinery is grouped by system to limit piping runs and to simplify construction and operation. The location of pumps and tanks therefore determines the locations of connected equipment. With similar logic, generators, switchboards, distribution panels, and transformers are arranged to limit cable runs. On the other hand, some machinery is grouped by type rather than by system, for example, fuel-oil J;'urifiers are often grouped with lubricating-oil purifiers to enable common facilities to be shared.

Access for operation, inspection, maintenance, repair, overhaul, and renewal is generally of paramount importance, with lifting gear, removal routes, and spare-parts storage all considered in the design process. Provision for removal ashore of such items as turbine and generator rotors, gear elements, large electric motors, and main-engine components, is typically required. Direct access routes for normal stores handling, usually using a ship's stores crane, are normally provided. Work areas are usually located close to equipment requiring frequent disassembly, including purifiers, strainers and filters, diesel-engine injectors, and boiler burners. A central machine shop is normally provided, and in keeping with the intended maintenance philosophy, may be extensively equipped, with designated areas for specific activities.

A central control station is typical whether or not machinery is normally attended or is fully automated. Generally this station is in a control room located in or immediately adjacent to the engine room, together with switchboards and distribution panels. In some ships with fully automated machinery, however, the machinery- control station is placed in an integrated ship-control center remote from the engine room.

Because of their high noise level, diesel generators are often isolated from the general machinery space by acoustic bulkheads. Gas turbines are usually fitted with acoustic enclosures.

Other machinery, for example, purifiers and fuel service systems, may be isolated to facilitate ventilation and fire suppression. To further minimize fire risks, oil tanks are not located over boilers or incinerators, or close to uptakes. Fire-hazardous equipment is kept clear of equipment critical to ship control and damage control. Fire pumps are kept distant from each other.

Large tanks in or adjacent to the engine room normally include those for fuel settling and service, lubricating-oil storage and treatment, and reserve-feed storage. Engine-room double-bottom tanks may be used for main-engine and reduction-gear oil sumps, distillate-fuel storage, reserve feed, waste oils, untreated bilge water, or ballast.

24.2.4 Criteria for Power Plant Selection

Characteristics of modern merchant -ship power plants that should be considered in selection of machinery are discussed below. A summary is presented as Table 24.1.

24.2.4.1 Acquisition cost

A marine power plant is a system comprised of components which include the main and auxiliary machinery, foundations, shafting, piping, ducting, cabli/g, automation and controls, access and overhauling gear, etc. The acquisition cost referred to here is the cost to the ship owner of the complete system, and includes the costs for components and materials, engineering, fabrication, installation, commissioning, and testing, including labor and overhead costs. Comparison of the total cost is clouded by such factors as different shipyard practices, labor costs in different regions, or the eagerness of component manufacturers to market their products. Deviation from a pre-existing local practice can have an overwhelming effect. If influences such as these could be removed, there would be little difference in acquisition cost for complete power plants that are of different type, as long as they are equal in their quality of outfit. With these caveats, acquisition costs for complete plants of equal outfit are likely to be within about ten percent of the mean. At all power levels, low-speed diesel plants and coal-fired steam plants are likely to have the highest acquisition costs. At lower power levels where high-speed diesel plants are practical, they generally have the lowest acquisition costs. As power levels rise progressively, the lowest acquisition cost is likely to be for medium-speed diesel plants. then for oil-fired steam plants, and then for simple-cycle gas-turbine plants.

Examples of changes in the quality of outfit that can disrupt the expected order of acquisition cost include changes in the level of automation, the addition of waste-heat recovery, the addition of an attached generator with speed or frequency regulation, or the use of a controllable-pitch propeller.

24.2.4.2 Margins and ratings

Diesel engines are normally selected to operate at an average power output of 70% to 90% of their maximum continuous rating (MCR). This practice helps to ensure that predicted ship performance will be achieved in service as the hull and propeller foul, and in rough seas, and is in keeping with expected lives of engine components. On the other hand, steam plants and gas turbines are often intended to deliver their maximum rated power continuously. As a result, if all else were equal, a ship with a diesel plant would appear to have more installed propulsion power than an otherwise identical ship with steam or gas turbines.

24.2.4.3 Type of fuel

Most ships' power plants use petroleum fuel oils. Distillate fuels (which include gas oil, No. 2-D, and DFM) are the easiest to use but are the most expensive, while residual fuels are the cheapest but most difficult to use. Intermediate fuels are produced by blending distillate fuels with residuals, and generally have all of the difficulties of residuals although to a reduced extent. Because of their lower density, distillate fuels are considered light fuels, with blended and residual fuels all being heavy fuels. The heaviest fuels must be heated to reduce their viscosity before they can be pumped, and all heavy fuels must be heated further before they can be burned. Heavy fuels generally contain impurities, including solid particles, water, sulfur, vanadium, and sodium, and tend to leave deposits of carbon during combustion, all of which contribute to the deterioration of the machinery. Distillate fuels contain little, if any, of these impurities, do not generally require heating, and do not normally leave carbon deposits. In addition, the heating value (the energy content) of the heaviest fuels is typically five or six percent below that of the distillates.

Low-speed diesel engines are more likely than the higher-speed engines to operate on heavy fuels without excessive maintenance costs. Most medium-speed engines are capable of operation on heavy fuels, although maintenance costs are almost always higher when compared to those of low-speed engines operated on heavy fuels, or in comparison to those of medium-speed engines operated on distillate fuels. Some medium-speed engiRes and all high-speed engines require distillate fuels. Oil-fired steamships are generally designed for residual fuel, but would have somewhat reduced maintenance requirements if lighter fuels are used. Some heavy-duty gas turbines have been operated successfully on carefully selected heavy fuels, and others are considered suitable for light-intermediate fuels. Aircraft-derivative gas turbines must be run on distillate fuel.

Even in power plants in which heavy fuels can be used, the choice of fuel is mostly an economic decision, requiring that a balance be struck between the lower cost of the heavier fuels and the inconvenience and increased costs of fuel treatment and machinery maintenance. The power plants of most sea going merchant ships are run on heavy fuels, but most coastal, river, and harbor craft, most fishing boats, and most naval vessels use distillate fuels.

Coal is used in some trades, where its much lower cost, well below that of even residual fuel oil, justifies the difficuities inherent in its use. Coal has lower heating value and density than fuel oil, resulting in much larger volumes and weight penalties for coal-fired ships than for oil-fired ships of similar range. Coal-fired ships are necessarily steam ships, with coal-storage arrangements, coal-transfer systems, and boilers all specifically designed for the particular grade of coal that will be used.

Where natural gas is available, it is an attractive fuel that bums cleanly in boilers, diesel engines, and gas turbines; reducing maintenance costs and exhaust emissions of atmospheric pollutants. Difficulties associated with natural gas for marine use are in the gas-storage and handling arrangements. Natural gas is the principal fuel for liquefied natural-gas carriers, where it is available as boil-off from the cargo. Because of the reduced exhaust emissions, natural gas use in coastal, river, and harbor craft is likely to increase.

24.2.4.4 Fuel consumption

Power plants are often compared on the basis of their specific fuel consumption, or SFC, which is the quantity of fuel consumed per unit of power delivered. It should be noted, however, that raw SFC data can be terribly deceptive, as the values usually cited for steam plants are all-purpose SFCs, on the intended fuel, and including transmission losses and margins, while those most often cited for diesel engines and gas turbines are for the engine alone, often on higher-quality fuel than will be used, and usually without transmission losses or margins. Allowances for these differences can easilyadd 15% to 20% to the quoted SFCs. For purposes of comparison, therefore, SFCs of diesel engines and gas turbines must be adjusted as explained below.

Typical values are cited in the following paragraphs for oil-fired plants, in units of grams of fuel per hour per kW. The coal consumption of coal-fired plants is not addressed iere because it is dependent on the heating value of the particular coal to be used, which varies widely among grades. With coal-burning methods currently used in marine boilers, they are about five percent less efficient than oil-fired boilers, but advanced coal-firing methods becoming well established ashore can redress this disparity. In addition, the parasitic loads of a coal-fired plant, principally for coal and ash handling, are greater than for oil, and are reflected in the all-purpose fuel consumption. Natural gas consumption rates are not discussed here because they are also case-specific, again depending on gas quality and on combustion technique. In general, when compared on the basis of energy consumption to their oil-fired counterparts, natural gas boilers, reciprocating engines, and gas turbines are similar in efficiency. However, efficiencies with natural gas are slightly higher for gas turbines if the firing temperature can be increased, and are slightly lower for some air-limited reciprocating engines.

The SFC for a steam plant is usually obtained from a heat balance performed in accord with a standard which ensures reasonable margins and allowances, which includes energy required for auxiliaries and ship's services, which includes transmission losses to the shaft power level, and which is based on the intended fuel, usually a residual fuel. The SFC is thus an all-purpose value, achievable in service on heavy fuel, as long as the plant is operated in general accord with the heat balance, and as long as it is well maintained. Multiplying the SFC of a steam plant by the shaft power gives a reasonably reliable value of the ship's fuel consumption.

Typical values of all-purpose SFC for geared steam-turbine plants run on heavy fuel, for the plant ratings stated, with the plant running within about 10% of its rating, are:

15000 skW or higher	260 to 300 g/skW-h
10 000 skW	280 to 320 g/skW-h
5000 skW	320 to 360 g/skW-h

For operation at part power the SFC is higher, as in Figure 24.5.

In contrast to steam plant practice, SFCs for diesel engines are usually given for distillate fuel, and may include a deduction referred to as the *tolerance.* These SFCs are usually based on brake power (without transmission losses) of the bare engine without attached auxiliaries. The values are only minimally affected by ambient conditions. To calculate the fuel consumption the SFCs of diesel engines may first have to be corrected by a factor of 1.02 to 1.03 to restore the *tolerance,* then further corrected by the ratio of fuel-heating value, up to 1.06 if the engine is to be run on heavy fuel. Then the brake power must be determined from the shaft power to the propeller: first by adding any gear- or shaft-driven loads, and then, for direct-connected, low-speed diesel engines, the total shaft power must be multiplied by about 1.005 for thrust bearing loss, to yield brake power supplied to the shaft; alternatively, for geared diesels the total shaft power is multiplied by about 1.02 to allow for gear losses (which include thrust bearing loss). Then the power to any attached loads driven directly by the engine must be added to yield the total brake power required from the engine. Finally, multiplying the total brake power by the corrected SFC yields the fuel consumption of the engine. However, the result is not the all-purpose fuel consumption of the plant unless electrical and heating needs are met by the attached generator or by waste-heat recovery. The additional fuel consumed by oil-fired boilers or independent diesel generators must be added.

Typical values of SFC for diesel engines, which must be adjusted as described previously, are:

low-speed diesels	160 to 180 glbkW-h
medium-speed diesels	165 to 210 glbkW-h
high-speed diesels	200 to 250 glbkW-h

In general, for each class of engine, the larger-bore, lower-rpm engines have SFCs near the bottom of the range, and smaller-bore engines, near the top. Diesel engines have fairly constant SFC above about 50% of their rating, as shown in Figure 24.4.

For gas turbines, SFCs are usually based on distillate fuel and on brake power, but are likely to include all directly driven accessory loads. (When the gas turbine is capable of operation on heavy fuel, the SFC will likely increase by more than the ratio of heating value, since the firing temperature may have to be reduced, a matter outside the scope of this chapter which will not be further addressed here.) The brake power must be determined from the shaft power to the propeller: first by adding any gear- or shaft-driven loads, and then, for geared turbines, the total shaft power is multiplied by about 1.02 to allow for gear and thrust-bearing losses. Multiplying the total brake power by the corrected SFC will yield the fuel consumption of the gas turbine. However, the result will not be the all-purpose fuel consumption of the plant unless electrical and heating needs are met by the attached generator or by waste-heat recovery. Additional fuel consumed by oil-fired boilers or independent diesel-generators must be added.

Typical values of SFC for simple-cycle gas turbines, which must be adjusted as described above, are shown in Figure 24.5. The values are adversely and significantly affected by high ambient temperatures and by high intake- and exhaust-duct losses.

When simple-cycle gas turbines are operated at part load, SFCs increase sharply, as shown in Figure 24.4.

An advanced gas turbine now under development with an intercooled compressor and a compact regenerator, with a rating of about 25 000 bkW, will offer an SFC of about 200 glbkW, approximately constant from about 40% rating to full power. This fuel-consumption pattern is similar to those of diesel engines, although without the ability to bum heavy fuels.

When electric drive is used instead of reduction gearing, fuel consumption is five to ten percent higher. See Figure 24.6.

Even after all the corrections are made, it is usually found that diesel plants have significantly lower fuel consumption than other power plants, with an economic effect likely to be heavily compounded when heavy fuels can be used.

24.2.4.5 Volume and Mass

The volume occupied by a ship's power plant is not important if the space is available in any event, as on large relatively slow ships with heavy cargoes, such as tankers and are carriers. These ships often have larger engine rooms than required, even when fitted with low-speed diesel engines. A similar situation obtains with deck-loaded ferries, where the hull is largely empty, leaving far more space than needed for the high-speed diesel engines that are likely to

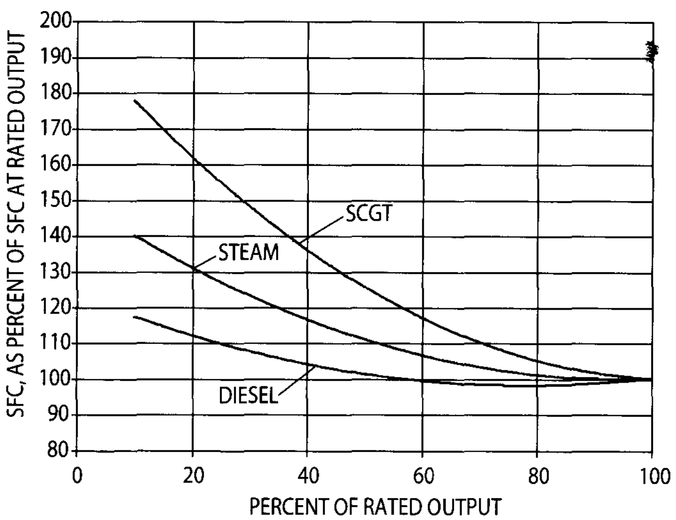

Figure 24.4 Variation in Specific Fuel Consumption (SFC) with Load for Steam Plants, Values Shown are for All-purpose Fuel Consumption; for All Others, Values are for the Engine Alone

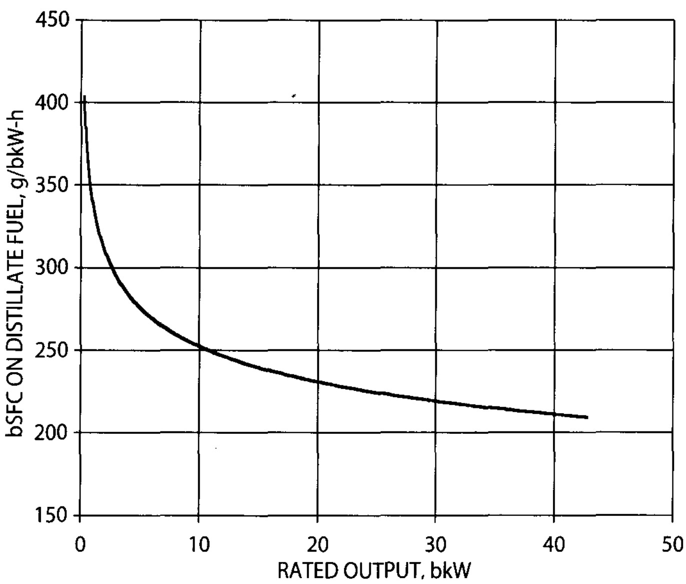

Figure 24.5 Typical Values of Brake Specific Fuel Consumption (bSFC) of Simple-cycle, Marine Gas Turbines Operated on Distillate Fuel, at Rated Conditions

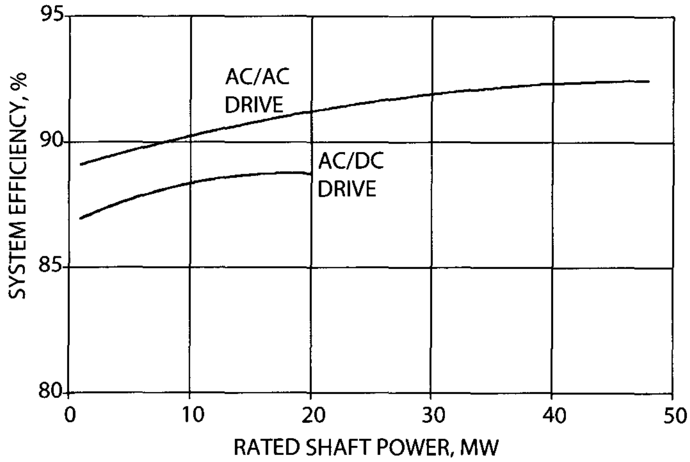

Figure 24.6 Electric Drive Efficiency at Rated Shaft Output (1)

TABLE 24.II Volume and Mass Guidelines

Power Plant	m^3/skW	*kg/skW*
low-speed diesel	0.35 to 0.7	60 to 130
medium-speed diesel	0.12 to 0.35	25 to 90
high-speed diesel	0.07 to 0.2	10 to 35
oil-fired steam	0.25 to 0.6	30 to 90
simple-cycle gas turbine	0.04 to 0.15	7 to 35

be used. The guideline values cited in Table 24.II are intended to indicate the gross engine-room volume required, and the total machinery mass. Gross engine-room volume is defined here as the volume from the tank top (or bottom shell, if there is no double-bottom) to the top of the engine room, including any trunk above the main deck, but excluding shaft alleys and casings (for intake and exhaust), while including space, as appropriate, for auxiliary machinery, workshops, control rooms, spares storage, and engine-room tankage, for efficient arrangements with typical auxiliary outfit. Total machinery mass, as used here, is the mass of the entire content of the machinery spaces, plus shafting, bearings, and propellers, including all auxiliaries, foundations, ducting, uptakes, piping, cables, engine-room ventilation, workshop equipment, control equipment, spares, and liquids contained in machinery and piping, but not including fuel in day tanks, settling tanks, or bunker ta;<.s.

For the diesel plants, the lower values in each range are appropriate for the higher-rpm engines with the most austere level of auxiliary outfit. For steam and gas turbine plants, the lower values are associated with the higher-powered plants. For a discussion of coal-fired plants, see Section 24.5.

An important point to consider when comparing mass and volume of these plants is the effect of fuel consumption, since stored fuel is not included in the values given above. For example, if machinery is heav:y or bulky but of high efficiency, the difference in the mass and volume of fuel necessary for a long voyage may yield a lower overall mass or volume.

24.2.4.6 Flexibility in arrangement

This term refers to the extent to which major machinery items can be shifted to accommodate constraints on engine-room proportions. Low-speed diesel plants represent one extreme in their lack of such flexibility: there must be one engine per shaft, mounted on the tank top, and aligned with the vertical and transverse center line of the propeller shafting. The length of the engine may determine the minimum length of the engine room. In addition, low-speed engines are very high, and minimum engine-room height is determined by adding the overhaul height to the height of the engine. Such height may be difficult to accommodate in a shallow hull, or it may interfere with arrangements of vehicle ramps of roll-on, roll-off ships.

On the other hand, considerable flexibility exists in steam-plant arrangements. For example, in contrast to the short engine room shown in Figure 24.3, a low engine room can be achieved by mounting the boilers forward of the turbines, on the tank top.

The power plants that offer the greatest flexibility in arrangement are usually electric drive, especially with high-speed diesel or gas turbine driven generators, which, because of their low weight, can be located almost anywhere aboard the vessel, including the superstructure.

24.2.4.7 Lubricating oil consumption

While small amounts of lubricating oil are lost in steam turbine and gas-turbine plants, all diesel engines actively consume lubricating oil in significant amounts. The following are guideline rates for specific oil consumption for all purposes for diesel engines of each type. Total oil consumption for a plant would include oil consumed by the main engines and the auxiliaries, including auxiliary engines:

low-speed diesels	0.5 to 1.1 g/bkW-h
medium- and high-speed diesels	0.7 to 1.7 g/bkW-h

Although lubricating oils are consumed at a much lower rate than fuel oil, lubricating-oil consumption is a significant operating-cost component because the unit costs of lubricating oils are usually five or ten times those of fuel oils.

24.2.4.8 Maintenance requirements

Maintenance requirements include inspections and trend monitoring, routine servicing, and overhauls, and involve costs for labor and parts, some accruing continuously, others concentrated at intervals. On a life-cycle basis, per unit of power output per unit time, the list below represents an attempt to rank marine power plants in order, from lowest maintenance cost to highest:

- oil-fired steam plant on residual fuel,
- any diesel plant on distillate fuel at modest output,
- low-speed diesel plant on heavy fuel at modest output,
- low-speed diesel plant on heavy fuel at high output,
- heavy-duty gas turbine plant on distillate fuel,
- coal-fired steam plant,
- medium-speed diesel plant on heavy fuel at modest output,
- medium-speed diesel plant on heavy fuel at high output,
- high-speed diesel plant on distillate fuel at high output, and
- aircraft-derivative gas turbine plant on distillate fuel.

Too many factors can affect the maintenance requirements for this list to be taken as more than guidance.

24.2.4.9 Manning and automation

Modem merchant -ship power plants of all types are normally built with sufficient automation for unattended routine operation at sea, under bridge control.

Traditional engine watches are normally not necessary, a major factor in enabling the low levels of manning that have come to be expected. Some older ships are not up to this standard. Exceptions among modem ships include those built to suit specific labor practices which inhibit reduced manning, some passenger vessels, and vessels that are operated in congested waters, or are so frequently maneuvered, that continuous watch standing is preferable,

With normally unattended machinery, engine-department crew levels are determined by the number necessary for occasional attendance during maneuvering or emergencies, who are thus normally available for routine tasks such as regular maintenance and inspection, fuel transfer, and record keeping. Even in a large and complex power plant, a chief engineer and one or two assistants may be sufficient, with additional help available when needed from dual-qualified officers and seamen who are normally assigned to deck watches. Under such circumstances increased use is made of contract work gangs for more major maintenance tasks in port, or even traveling with the ship for parts of a voyage.

24.2.5 Electric Drive versus Gearing

Overall efficiencies of electric-drive systems are shown in Figure 24.6; for comparison, gearing efficiencies are on the order of 98% to 99%. Gearing is also lighter and less expensive. However, electric drive offers certain advantages:

- precise speed control;
- rapid reversing, with full power available astern;
- high torque at low rpm;
- flexible machinery arrangements;
- ability to combine the output of multiple prime movers; and
- flexible load management.

The last items listed are particularly useful where the power requirement for the ship's mission or trade rivals or exceeds the propulsion load, so that the effect of high propulsion losses is diminished. With multiple generating sets, the number in use can be matched to the load, enabling each to be run close to its best efficiency, further compensating for transmission losses.

With reference to Figure 24.6, when the incentives for electric drive include speed control and high torque at low speed, as might be the case with research ships, ice breakers, cable layers, and commuter ferries, AC/DC drive is the likely choice. Shuttle tankers, long-distance ferries, and passenger ships are candidates for AC/AC drive.

24.2.6 Controllable-pitch Propellers

Compared to fixed-pitch propellers, controllable-pitch propellers are much more expensive, more complex, and less efficient at their design rpm. However, because the thrust can be varied independently of rpm, from full ahead to full astern, controllable-pitch propellers offer advantages that can justify their use in ships of all types. These advantages include the following:

- Maximum thrusLis available at low ship speed, which is especially helpful for tugboats and trawlers with diesel engines, and for icebreakers with diesel engines or gas turbines.
- The propeller pitch can be adjusted to match different prime movers clutched to its drive shaft. This feature facilitates combined diesel or gas turbine plants, and enables single-engine operation of diesel plants with paired engines geared to a single screw.
- The propeller can provide reversing capability for nonreversing engines, which is particularly useful for gas turbines.
- Rapid maneuvering is possible without stopping the engines or using clutches.
- Since shaft rpm can be held constant, independent of ship speed, attached generators can supply electricity at constant frequency without constant-speed transmissions or frequency-rectification equipment.

Controllable-pitch propellers are normally flanged to their propeller shafts, which are therefore drawn outboard, an operation which might require removal of the rudder. The shafting is hollow to accommodate the hydraulic lines or rods that operate the hub.

24.2.7 Waterjets

Waterjets offer advantages over propellers in some cases. For shallow-draft vessels, the impeller of a water jet can be more easily protected from foreign-object damage than a propeller. For high-speed vessels, water jets can be more efficient than propellers, in part because of better hydrodynamic performance of the hull forms that are possible with water jets, but not with propellers.

Waterjets are usually fitted with rotating nozzles or thrust deflectors for steering, making rudders unnecessary. Generally, they are also fitted with thrust-reversing deflectors, eliminating the need for reversing gearing or engines. Nevertheless, reversing gears are sometimes fitted when water jets are used for shallow-draft vessels, to enable back flushing of the intake.

The range of waterjet rpm at rated performance is from over 3000 rpm at the lowest power levels, to about 500 rpm for high-power applications. Direct-drive from medium and high-speed diesel engines is possible, although optimum performance of both the water jet and the diesel engine usually requires reduction gears. For gas-turbine drive, reduction gears are normally necessary.

24.2.8 Electrical Generating Plant

Regulatory-body requirements generally demand a minimum oftwo ship's service generators, each of sufficien1i..capacity to carry the essential sea load. For ocean-going s~ps, conservative practice calls for an increase in the number of ship's service generators to at least three, one or two of which should be driven independently of the main propulsion plant, usually by diesel engines. These ship's service generators are in addition to the emergency source (usually another generator), which must be self contained and located outside of the engine room.

An attached generator can serve as a ship's normal source of electricity at sea, as an alternative to one ship's service generator. A main engine may drive an attached generator directly or via the reduction gear or the propeller shaft. The concept is applicable to plants of any size or type, although, for circumstantial rather than technical reasons, it has seen widespread use only for diesel plants. Two considerations are, first, the provision of an immediately available standby source to allow for unanticipated maneuvering or stopping of the main engine, and second, a means of maintaining constant frequency. Both issues can be resolved with additional equipment. Increases in acquisition cost and plant mass will be significant if the main-engine rating must be higher to accommodate the attached generator, and especially if frequency or speed correction is necessary, but fuel costs will be reduced. If the alternative normal source is a continuously run diesel generator, maintenance costs are likely to be reduced as well.

24.3 DIESEL PLANTS

While Section 24.1 provided information that might lead to a selection of diesel machinery over steam or gas turbines, and perhaps towards a preference for low-speed or higher-speed engines, this section addresses significant characteristics of diesel plants that must then be considered.

24.3.1 Review of Engine Types

To summarize and amplify the information in Section 24.1, diesel engines fall into either a low-speed category or the medium- and high-speed categories. Low-speed engines are generally intended for the direct drive of ships' propellers without any speed-changing device and are therefore restricted to an rpm range for which efficient propellers can be designed, generally well below 300 rpm and possibly as low as 55 rpm at rated power. Low-speed engines are classified as two-stroke, crosshead engines. They normally have four to twelve cylinders in-line, and are always turbocharged. These engines are heavy and very large, but they are well suited to operation on low-quality fuels and generally require only modest levels of maintenance.

Medium- and high-speed engines, because of their higher rpm, must drive propellers through reduction gearing or by electric drive. With few exceptions, these are four-stroke, trunk-piston engines, which have up to ten cylinders in-line or up to 24 in a V-configuration. Most are turbocharged. The upper limit of the medium-speed category, and the start of the high-speed category, is generally placed in the vicinity 1200 rpm, but there are no clear physical features that enable the distinction to be made. These engines tend to be lighter, more compact, and lower in acquisition cost than low-speed engines of comparable power output. Many of these engines have a proven heavy- fuel capability, but most evidence indicates that maintenance costs are higher than those of low-speed engines that are run on fuels of similar poor quality. Some engines, especially those in the higher-speed category, are restricted to distillate fuels.

A notable exception to the typical characteristics of low-speed engines is a group of four-stroke, trunk-piston engines that are designed to be directly connected to propellers. This class of engine is indigenous, in both manufacture and application, to the Far East. These engines are built with six or eight in-line cylinders; they are rated for 70 to 700 kW per cylinder at speeds of 200 to 500 rpm.

A notable and common exception in the medium- and high-speed category is the series of two-stroke, trunk-piston, medium-speed engines produced in turbocharged and mechanically blown versions that dominate their field of application in American waters, despite their requirement for distillate fuels; these are built only in a V-configuration. The highest rated of these engines, with twenty cylinders, has an output of more than 3500 kW at 900 rpm.

24.3.2 Margins and Rating

24.3.2.1 Engine ratings

The rating of an engine is generally given as a continuous power output at a specified engine speed, and is usually called the maximum continuous rating (MCR). The rating reflects the confidence of the manufacturer and the regulatory bodies that the engine is capable of reliable performance at that level. However, if reasonably long component lives and service intervals are to be achieved, the engine will have to be matched to its load so that, on average, substantially less than the MCR is normally delivered. Such considerations sometimes lead to the definition of a continuous service rating that is perhaps 80% to 90 % of the MCR.

An engine may be given different ratings for different applications, for example, a high-performance rating may be given to an engine that is intended for an application in which the engine may be operated under conditions of sustained high power for limited periods of time, but witlI reduced intervals between overhauls. This might be in cOli'trast to a lower rating assigned to the same engine for a different application, where the engine will be operated for long periods at a more modest power output, and with longer component lives and service intervals. The MCR of any particular model of engine may be increased over time to reflect component improvements or service experience.

An engine may be *derated,* that is, assigned a rating lower than normal, to optimize it for a particular application, usually to reduce maintenance costs, to reduce fuel consumption, or most important for low-speed engines, to a lower rpm to permit the use of a propeller of higher efficiency. However, a derated engine will be larger, heavier, and have higher acquisition cost than an alternative engine that provides the required power at its normal rating. Derating mayor may not result in engine components that are different from the standard design, but as long as auxiliaries, shafting, and reduction gearing are based on the reduced engine rating, there is limited likelihood that a derated engine could be rerated to its normal rating.

24.3.2.2 Limits of engine performance

Limits defining the operating envelope for an engine are identified in Figure 24.7. Limited operation outside the operating envelope will generally result in decreased component durability, which is reflected in increased requirements for inspection and maintenance. A catastrophic failure of a properly maintained engine under these conditions is unlikely because of the design margins, and because periodic scheduled inspections reveal such effects as burning, cracking, or distortion in time for component renewal. The mean effective pressure (MEP) is a parameter that expresses limiting air availability and thermal stress on an engine. The MEP is directly proportional to the torque that is applied to the driven load, so that the product ofMEP and rpm is directly proportional to brake power output. Therefore, as Figure 24.7 shows, within the limit of rated MEP, an engine can achieve its rated power output only at, or above, its rated rpm; at a lower rpm the power that an engine can develop is limited by the MEP, or torque. Sustained operation above rated MEP is likely to result in poor combustion, carbon deposits, smoke, high exhaust gas temperatures, high metal temperatures, and reduced component lives.

An important characteristic to note is that the engine can be forced into a condition of excessive torque and MEP without exceeding rated power if the engine is forced to run at reduced rpm.

Minimum engine rpm is typically 25% to 40% of rated rpm, below which operation would be erratic, with poor combustion resulting iq carbon accumulations. Except when

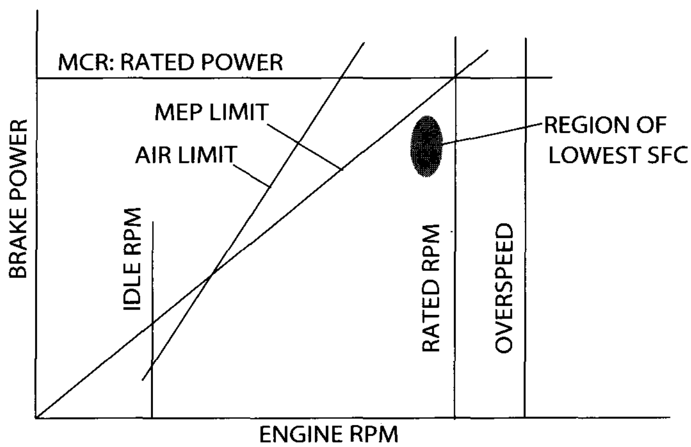

Figure 24.7 Diesel-engine Performance Limits

an engine that drives a fixed-pitch propeller is run at a modest overspeed on trials in order to maximize the load, operation beyond rated rpm is unusual.

Generally, diesel engines are so matched to their loads that the power delivered in service is in the range of 80% to 90% of the MCR. This region of operation usually coincides with the lowest specific fuel-consumption, and with anticipated component lives and service intervals. The difference between the power at MCR and the power level established for normal operation in service is the engine margin.

24.3.2.3 Matching engine to propulsion requirement

In Figure 24.8, a ship's speed-power curves are superimposed on the engine-performance curves of Figure 24.7. The curve labeled *average ship performance in service* reflects the fact that more power is required for a given ship speed to be achieved in service than on trials by an amount called the service margin. An engine is normally limited in its power output by the constraints on air availability and thermal overload that are expressed as the MEP limit.

The MEP, like the torque, is proportional to the power developed divided by the rpm. If the ship is operated initially in service at a certain speed corresponding to an rpm below the rated rpm of the engine then, as the hull resistance increases in service, more power is required to maintain the same propeller rpm, and the MEP progressively increases. Eventually the MEP limit is reached, and rpm must thereafter be progressively reduced as the hull resistance continues to rise.

If an engine were matched to deliver its full MCR at trial speed when the hull is clean, then in service, as the hull fouls, the engine would reach its limiting MEP sooner.

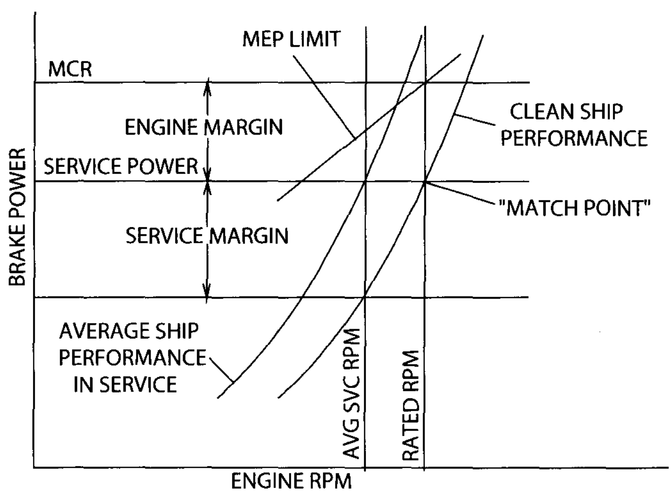

Figure 24.8 Diesel-engine Performance Map with Ship Speed-power Curves Superimposed

The rpm of a fixed-pitch propeller is almost directly proportional to the ship speed at a particular draft and trim at any given time, but in service, as the hull and propeller roughen and foul and drag increases, the rpm required at any given ship speed rises slightly (the slip increases). This trend is beneficial in terms of power available, as it diminishes the rate at which MEP rises as the hull fouls.

The difference between the MCR and the power required to achieve service speed on trials is therefore a total power reserve, and, from Figure 24.8, is equal to the sum of the engine margin and the service margin. In practice, the power reserve that is incorporated in the engine margin up to the limiting MEP is available to meet required service speeds as the hull performance deteriorates and as sea conditions worsen.

In fact, the division between engine margin and service margin is not consistently defined, since the continuous service power is arbitrarily determined. The important consideration is that the total margin must be adequate if the ship is to achieve its expected performance.

To select an engine for a particular ship, the power required to drive the propeller, allowing for transmission and shafting losses, at loaded draft and trim, with the hull and propeller clean, plus the power required by attached auxiliaries, is divided by an appropriate *match point* percentage, typically 80% to 90%. An engine is selected which can deliver the resulting power at its MCR, at its rated rpm. A match point of 80% to 90% will usually result in adequate margins, but a lower value is appropriate if:

- the ship must maintain rigorous schedules;
- the long-term effects of increased hull and propeller roughness and fouling are expected to be large;
- the ship is expected. to be drydocked infrequently;
- a large allowance for adverse weather conditions is necessary; or
- the intended trade will take the ship into warm seawater ports or anchorages, where increased hull fouling is likely, for extended stays.

The higher the MCR of the selected engine relative to the power required at rated rpm under trial conditions (that is, the lower the match point), the higher will be the average power output that can be utilized in service. The higher average power output will enable higher ship speeds to be achieved. However, more power must be installed, and so acquisition cost and plant weight will be higher. As a further consequence, in single-screw, single-engine installations, even ifthe ship can be ballasted down to loaded draft on trials, it may not be feasible to achieve MCR without overspeeding the engine.

24.3.3 Moments, Forces, and Vibrations

The loads imposed by a diesel engine on its foundation and on connected equipment are disturbances that are predictable in nature, amplitude, and frequency, and are among the data available from the manufacturer. Whether trouble will arise depends on the response of connected structure and equipment to these disturbances. If the frequency of a disturbance, or of any of its harmonics, is close to the natural frequency of connected structure or equipment, then even a disturbance of small magnitude can excite a resonant response.

Engine-imposed disturbances may be divided between, 1) external forces and moments, which can excite a response from hull structure, and 2) torsional vibration in the propulsion drive train, which usually affects only shaft-connected equipment. Generally, forces and moments internal to an engine are absorbed by the engine itself.

The frequencies of engine-imposed disturbances are related to the rpm of the engine, and are defined relative to that rpm by their order; i.e., their frequency as a multiple of engine rpm. Fractional orders are encountered in the case of four-stroke engines.

24.3.3.1 External forces and moments

External forces and moments arise from the reciprocating motion of the pistons and running gear, and would cause an unrestrained engine to pitch, yaw, roll, or rack. With the engine installed in the ship, these disturbances can excite a response from the hull structure. If necessary, the first- and second-order components of the pitching and yawing disturbances can be countered, completely or in part, with additional counterweights on the crankshaft or on balance shafts carrying pairs of opposed counterweights rotating in opposite directions, often driven by the engine itselJ. The larger, low-order components of roll couples and racking moments can be countered by horizontal bracing to adjacent structure. Higher-order components of the disturbances are usually, though not always, of sufficiently low magnitude to be left uncorrected.

External forces and moments are summarized below for typical marine diesel in-line engines without additional counterweights.

For two-stroke in-line engines:

- four-cylinder engines usually have severe first and second-order pitching couples and a severe fourth-order roll couple;
- five-cylinder engines usually have a moderate first-order pitching couple, but severe second-order pitching and fifth-order roll couples;
- six-cylinder engines usually have no first-order pitching couple, but a severe second-order pitching couple and a severe sixth-order roll couple;
- engines with seven or more cylinders usually have moderate or negligible first- and second-order pitching couples and moderate roll couples at an order equal to the number of cylinders; and
- eight- and twelve-cylinder engines may have racking moments in the horizontal planes sufficient to require countermeasures, typically at third, fourth, and fifth orders.

For four-stroke in-line engines:

- four-cylinder engines usually have a severe second-order vertical force, and a severe second-order roll couple;
- five-cylinder engines usually have a moderate first-order pitching couple, but a severe second-order pitching couple and a severe 2.S-order roll couple; and
- engines with six or more cylinders usually have moderate or negligible first- and second-order couples and moderate roll couples at an order equal to half the number of cylinders.

For four-stroke V-engines:

- eight-cylinder engines are balanced in regard to first and second-order pitching and yawing couples only if the bank angle is equal to the firing interval of 90 degrees; the smaller bank angles that are more common in marine engines can result in first-order disturbances sufficient to require correction;
- ten-cylinder engines usually have moderate first and second-order pitching and yawing couples and a moderate 2.S-order roll couple;
- 12, 16, and 24-cylinder engines are generally balanced in regard to low-order pitching and yawing couples, but have moderate roll couples at an order equal to a quarter of the number of cylinders; and
- 24, 18, and 20-cylinder engines usually have moderate or negligible first- and second-order pitching and yawing couples as well as moderate roll couples.

Two-stroke V-engines in marine propulsion service are predominantly of a single design, built only as V8, V12, V16, and V20 engines. These engines have no first- or second-order disturbances by design, which includes the use of camshaft counterweights.

24.3.3.2 Torsional vibration

Torsional vibration arises from a periodically varying torque superimposed on the steady torque being transmitted by an engine to its load. The sources of this varying torque include the discrete power strokes of the engine, which generate torque pulsations once per crank throw per cycle, and at higher orders of this frequency. In ships with direct-connected low-speed diesels, this is usually the dominant source of torque variation. Torsional-vibration calculations are required at an early stage in the design process, as soon as the engine has been selected and the configuration of the rotating system, including shafting, couplings, clutches, gearing, bearings, and propeller, is known. The rotating system may be susceptible to low-frequency excitation, such as that produced when a cylinder is taken out of service. Consequently, torsional vibration calculations are usually required for operation with a cylinder out of service, and additional barred speed ranges then may be imposed.

24.3.4 Electrical Generating Plant

While the usual prime mover for a ship's service generator in a diesel plant is a diesel engine, refinements and alternatives are described under separate headings in the following.

In the simplest case, all ship's service generators will be identical to simplify maintenance and provide flexibility in operation. Generally, one generator is normally in service, with at least one diesel generator on automatic standby. During maneuvering periods two diesel generators may be run in parallel. Peak loads are met by operating two or more generators. Because diesel generators should not be loaded to less than about 35% of their rated output in sustained operation, where there is a disparity between loads at sea and in port, or between loads on one leg of a voyage and another, differently rated units may be installed to meet the differing demands, or units might be operated in parallel routinely during periods of high demand.

Because of the high noise level of diesel generators, and because one or more will be running in port even when the main plant is available for maintenance, diesel generarors are often located behind an acoustic partition or in a separated machinery space.

24.3.4.1 Heavy fuel

Where ship's service diesel generators are to be the normal electrical source, there is often an economic incentive to fit generator engines suitable for heavy fuel, with the necessary support systems. There will be increases in acquisition cost, plant mass and volume, and maintenance requirements.

24.3.4.2 Steam turbogenerator

Where the main-engine output is large enough and/or the electrical needs are sufficiently limited, enough steam can be generated by the main engine exhaust gases in a waste-heat boiler to enable a turbogenerator to serve as one of the ship's service generators. Even where the turbogenerator can meet only part of the demand with steam from the waste-heat boiler, it may still be economically justified, with the balance of the electrical demand met by supplemental steam from oil-fired boilers, or with an attached generator or diesel generators. In addition to the reduction in fuel consumption, a properly designed and maintained waste-heat steam plant can have lower maintenance costs than a continuously run diesel generator. Increases in acquisition cost, plant complexity, mass (especially the topside mass of the boiler) and volume are likely to be significant.

24.3.4.3 Attached generator

An attached generator driven from the main engine, the reduction gear, or the line shaft can serve as a ship's normal supply, as discussed above in Section 24.1.

It is feasible to combine prime movers for a single ship's service generator. An example is an attached generator driven through a constant output-speed transmission by the main engine, which also accommodates input from a waste-heat steam turbine.

24.3.5 Steam Generating Plant

Most diesel plants of significant size are fitted with waste-heat recovery systems to generate steam for heating requirements, which are likely to include heating of heavy fuel, as well as hotel needs and heating of lubricating oil. (An alternative to steam is a thermal-fluid system, often used on uninspected vessels.) Where sufficient waste-heat is available, a waste-heat turbo generator may be fitted (see item 2 above). The waste-heat boiler and oil-fired boilers are integrated into the steam system, which is usually designed to function automatically to maintain steam pressure even as the main engine is maneuvered or stopped. On tankers, where steam may be required for cargo heating, cargo and ballast pumping, and for tank cleaning, and in any plant where maximum heat recovery is intended, the steam plant can be very sophisticated. Despite the automation, routine procedures are necessary to avoid corrosion, to maintain water quality, and to avoid soot accumulation that can lead to uptake fires. Neglect of these simple procedures has sometimes resulted in failures, giving the steam systems of diesel plants an undeserved reputation for unreliability.

24.3.6 Fuel and Lubricating Oil Tankage

Diesel plants on ocean-going ships, especially those using heavy fuel, usually require tankage for a diverse range of fuel and lubricating oils, within or adjacent to the engine room.

24.3.6.1 Fuel oils

Before fuel is used in a diesel engine on a large or ocean-going ship, it is normally passed through centrifugal separators, necessitating a two-stage handling procedure. Fuel is first transferred from bunker tanks distributed through the vessel to a settling tank, where it is held, undisturbed, long enough for most solids and water to precipitate. It is then passed through the separators to the day tank, from which the engine is supplied. The settling and day tanks are usually of 24-hour capacity. To enable gravity flow to the pumps and separators, the tanks must be at or above floor-plate level.

When heavy fuel is used, two settling tanks are preferred, so that one can remain undisturbed after filling, while the other is in use. The fuel in the settling tanks is heated, and to avoid convection currents caused by cold surfaces, the tanks should be separated from the side shell.

When multiple grades of fuel are used, for example, if the ship's service generators are run on distillate fuel while the main engine is run on heavy fuel, settling and day tanks must be provided for each grade. Even when all engines are normally run on heavy fuels, storage must be provided for distillate fuel, typically equivalent to a three-day supply for the main engine, to be used when maintenance practices, exhaust emission controls, or other operational considerations dictate.

24.3.6.2 Lubricating oils

Lubricating-oil storage tanks must be located above the tank top, and below a weather deck to facilitate filling, but are most often located on an upper flat within the engine room.

Low-speed diesel engines require two types of lubricating oil: cylinder oil, which accounts for most ofthe oil consumed (see 24.2.4.7), and system oil. A three- to six-month supply of cylinder oil is typical, stored in two tanks to atI0w two grades of cylinder oil to be carried.

Different diesel engines require different grades of system oil. In particular, main-engine system oil will most likely be different from that of ship's service generator engines. Ocean-going ships carry sufficient system oil to refill the system or drain tank of each engine at least once, plus sufficient margin to meet miscellaneous consumption.

System oil in all diesel engines drains to a sump at the base of the engine. In high-speed engines and in the smaller medium-speed engines, the oil is recirculated directly from this sump, but in larger engines the oil then drains to a separate tank, built into the double bottom directly below the engine, but separated from the bottom shell by a cofferdam. The capacity of this drain tank may be on the order of 0.5 to 1.0 kg/bkW of engine rating. Drain tanks are shown in Figures 24.10 and 24.11 as integral parts of the foundations. For medium- and high-speed engines, the system oil is periodically replaced, and stored quantities might have to be increased to reflect this requirement.

To accommodate the oil drained from medium- and high-speed engines until it can be discharged ashore, there must be a used-oil tank located low in the engine room. For low-speed engines, and sometimes for medium-speed engines, there will be a settling tank, equal to the capacity of the drain tank, but normally empty, to store oil replaced but suitable for re-use after treatment on board. The settling tank is usually located adjacent to the system-oil storage tank to simplify piping.

In addition to main and auxiliary engines, other equipment that may require oil to be stored in sufficient quantity to justify fixed tanks might include reduction gearing and stem tubes.

24.3.7 Intake and Exhaust Considerations

Diesel engines are best supplied with intake air at weather-ambient pressure and near weather-ambient temperature, free of excess moisture. The quantity required will be in the range of 6 to 8 m3/kW-h. In the usual arrangement, main and auxiliary engines draw air directly from the engine room. The engine room ventilation system is designed to deliver fresh air to the vicinity of the engine intakes, and vent fans and ducts must be sized to deliver the engine-intake air in addition to the ventilation air. When the engine room is small relative to the intake-air requirement, a direct intake from the weather may be justified. In this case, engine performance will benefit from the lower air temperature, but will be adversely affected by excessive intake-duct pressure losses.

The source of the air supplied to the engines must be located to preclude intake of exhaust gas, ventilation-system exhaust air, seawater spray, or flammable vapor from tank vents or other sources.

Each engine must have its own independent exhaust uptake led to the weather, as must each boiler and each incinerator. Except on smaller vessels where engine exhaust is piped overboard through the side shell or transom, all of the uptakes are led through the casing and through the top of the smokestack.

24.3.8 Maintenance Considerations

Diesel engines, especially those operated on heavy fuels, require considerable maintenance. In general, major machinery maintenance tasks aboard ship are staggered to provide a manageable amount of work during each port visit. Classification societies offer continuous machinery survey provisions to suit this practice. On the other hand, operators of ships in seasonal trades usually attempt to restrict all planned maintenance to the lay-up period, when complete overhauls are more conveniently undertaken.

Major engine maintenance involves disassembly. For all but small high-speed engines, mechanical lifting gear is necessary, and designated landing and storage areas, designated access routes from weather decks, and sufficient room for access must be allotted in the early design stages. Sufficient height must be provided over the main and auxiliary engines to remove the pistons. Main engines that are tall relative to the depth of the hull may require a trunk above the main deck level. For large main engines, a gantry crane is installed overhead. Lifting beams with trolleys are fitted for smaller engines, including diesel generators. At least one of the ship's stores cranes should be arranged to allow the direct transfer of parts and stores to the storeroom levels of the engine room, often through a hatch on deck and a vertical trunk.

For ocean-going ships, a considerable inventory of spare parts and special tools and equipment will be carried on board, most often stored or installed in the vicinity of the engines. Selected spares are kept in an overhauled, partly assembled condition, ready for use, to expedite both emergency repairs and staggered maintenance schedules. A used component that is withdrawn from the engine is either reconditioned to become the next spare or is scrapped.

24.3.9 Maneuvering Considerations

Diesel engines can provide equal torque and power to the propeller whether it is running ahead or astern, and the propeller must be designed to accept this load.

Diesel engines cannot be run reliably at speeds below about 25% to 40% of their rated rpm. Therefore, in fixed-pitch propeller installations, dead-slow speeds must be achieved by alternately running the engine at this spe~ and then coasting. For ships operated for extended periods at dead-slow speeds, a controllable-pitch propeller may be justified.

24.4 GAS TURBINES

24.4.1 Aircraft-derivative Gas Turbines versus Heavy-duty Gas Turbines

Although aircraft-derivative gas turbines (ADGTs) and heavy-duty gas turbines (HDGTs) run on the same basic thermodynamic cycle and have the same general configuration, they differ in performance parameters and design philosophy. The emphasis in aircraft engines is on high power~to-weight ratios and therefore on high performance. Expensive materials and manufacturing processes may be required, and limited component lives with frequent rebuilding may be necessary, relative to the simpler but more robust heavy-duty designs. In the aircraft application, there is no consideration of any fuel but the cleanest distillate, or of add-on equipment to utilize waste heat. These characteristics carry through to the ADGTs used for ship propulsion. However, the high power density, low specific weight, and stand-alone features of ADGTs, which have established them as the preferred prime mover for many naval vessels, are attractive characteristics for some commercial vessels as well, despite the relatively short component life and high fuel-quality requirement.

HDGTs are designed without the emphasis on low weight, which results in easier operating conditions and more robust, simpler components, with longer lives and a higher tolerance for fuel quality. The lower performance parameters for which HDGTs are designed encourage the use of added-on heat-recovery equipment, but result in high fuel consumption for simple-cycle HDGTs, relative to ADGTs.

24.4.2 Regenerative-cycle and Combined-cycle Gas Turbines versus Simple-cycle Gas Turbines

The high temperature, and therefore high energy, of gas turbine exhaust gas makes waste-heat recovery attractive in the right circumstances. In simple-cycle gas turbines, the exhaust heat is not recovered, or it may be recovered for auxiliary use. If the waste heat is returned to the cycle, or otherwise added to the shaft power of the gas turbine, it will improve the efficiency and fuel consumption significantly, especially at part-power levels. Examples of heat-recovery gas turbines include recuperative cycles (also called regenerative cycles) for HDGTs, intercooled-regenerative cycle ADGTs, and combint<d cycles in which the exhaust gas is used to generate steam for a steam turbine, the output of which is then combined with that of the gas turbine. However, any of these improvements must be traded-off against the added weight, the reduced power density, and the higher complexity, all of which are in contradiction to the usual reasons for using gas turbines in the first place. In addition, initial cost and maintenance requirements will be increased.

In general, the heat-recovery gas-turbine plant does not have the advantages of the simple-cycle gas-turbine plant in power density, specific weight, or simplicity; nor does it have the advantages of the diesel plants in fuel consumption or fuel-quality tolerance.

24.4.3 Intake and Exhaust Considerations

Gas turbine power output and specific fuel-consumption both suffer significantly from high intake-air temperature and depressed intake pressure. The large quantities of air required, typically 10 to 20 m3/kW-h, must be drawn directly from the weather. The inlet must be carefully situated to minimize ingestion of seawater spray. A location high on the ship is usually sought for this reason, and filters and baffles are fitted for removal of water droplets as well as solids. To minimize pressure drop in the duct, it must have a fairly straight run and must be large enough to limit velocities to 12 to 23 mls. The straight run and large size make the duct suitable as a removal path for the gas turbine when a unit exchange is necessary (see 24.4.4). Often, intake ducts are fitted with a porous or mesh acoustic lining, and silencing baffles may be fitted (which must be removed for unit exchange).

Power output and specific fuel consumption both suffer from back pressure at the exhaust. Exhaust temperatures for most gas turbines are 450 to 600°C, so that the volumetric flow will be some 2.5 to 3 times that of the intake flow. Exhaust ducts are usually sized for a maximum velocity of about 45 to 60 mls. Exhaust ducts are usually fairly straight, usually of circular cross-section, and generally of stainless steel. Exhaust ducts are commonly lined internally for sound reduction and thermal insulation, and silencing baffles may be fitted. The temperature-suppression equipment often fitted to exhaust outlets of naval-vessel gas turbines, to reduce their thermal signature, would not be fitted in commercial applications.

Because of the inevitable proximity of the air intake and exhaust outlet, care must be taken that the exhaust gas cannot be drawn into the intake.

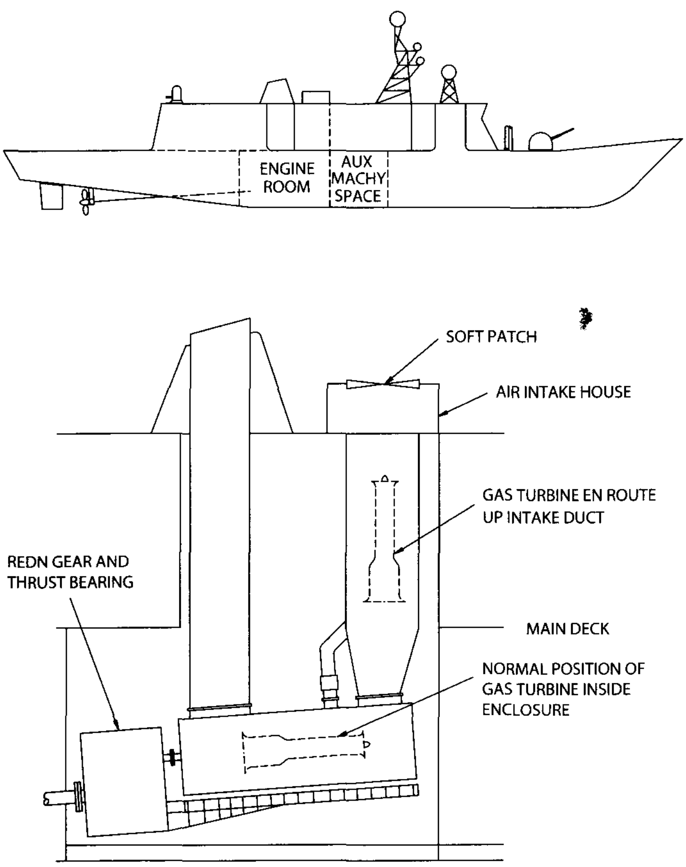

Figure 24.9 Frigate, showing Gas Generator Removal via Intake Duct

24.4.4 Maintenance by Replacement

In the concept of maintenance by replacement, a complete unit is removed from the ship and is exchanged with an already-rebuilt unit. This concept has proven to be particularly adaptable to the ADGTs in naval vessels, and is likely to prove equally desirable in many high-performance commercial vessels, for these reasons:

- the ship's crew is relieved of many routine maintenance tasks better handled by trained technicians in specialized facilities ashore;
- time out-of-service is minimized;
- the large air-intake duct provides a natural removal route, as shown in Figure 24.9;
- an ADGT is compact, light, and easily handled.

The ship and gas turbine installation are designed for maintenance by replacement from the beginning, with easily disconnected piping, wiring, and mechanical attachments, and with rails or pad eyes in the ducts, and access hatches at the intake.

24.4.5 Combined Prime Movers

A gas turbine is often combined with another gas turbine or a diesel engine to drive the same propeller shaft. Some of the more common configurations are listed below:

- two gas turbines, usually identical, operated together to achieve high ship speeds, in an arrangement called COGAG, for COmbined Gas turbine And Gas turbine,
- two gas turbines, one a small engine of low rating for cruising speeds, the other a high-powered gas turbine for high speeds, in a COGOG arrangement, for COmbined Gas turbine Or Gas turbine, and
- a diesel cruise engine, and a high-powered gas turbine for high speeds, in a CODOG arrangement for COmbined Diesel Or Gas turbine.

Usually, a controllable-pitch propeller is fitted with these arrangements in order to match the different operating conditions for each prime mover.

In addition to providing a measure of redundancy, and, for COGAG systems, providing high total power, the advantages of combined prime-mover plants are principally in fuel consumption at part power. A small gas turbine operated at high power is likely to be more efficient than a large gas turbine operated at part power (see Figures 24.4 and 24.5), while a diesel engine is even more efficient.

24.4.6 Reversing Arrangements

Reverse thrust for ships with gas-turbine propulsion may be provided by controllable-pitch propellers, by water jets, by electric drive, or by reversing gearing.

24.5 STEAM PLANTS

24.5.1 Reasons for Continued Use of Steam Plants

Despite the high fuel consumption of steam plants relative to diesel plants, many steam ships remain in service, and new steam ships continue to be ordered, for reasons that depend on the specific application. Some examples are listed below:

- at moderate fuel prices, the fuel-cost savings of a diesel ship will take many years to balance the cost of a replacement vessel or of a conversion. Thus there may be little economic incentive to a ship owner to shift away from continued operation of an existing steamship. This situation is particularly true in trades restricted to U.S.-built or U.S.-flag ships, since most U.S.-flag ships were built as steamships well into the 1970s. In some cases the economic circumstances have justified extensive hull reconstruction and machinery modernization, but not new construction or conversion to diesel propulsi0I)
- coal is a low-cost fuel wherever it is available in abundant supply, cheaper than even residual fuel oil. Coal-fired ships using established technology are necessarily steam ships,
- all currently operating and all recently built LNG ships are steamships. Economic considerations generally dictate that the boiled-off cargo be consumed as fuel, rather than be re-liquefied. While natural gas is an excellent fuel for both diesel engines and gas turbines, and while the technology exists for the disposal of the boiled-off gas while maneuvering or in port, these plants would still be innovative for the trade. On the other hand, the gas-fired steam plants are highly evolved and represent the safe, well-established, low-risk choice. However, the potential savings in fuel cost may eventually provide sufficient incentive for a change, and
- nuclear propulsion is considered to be beyond the scope of this chapter, but it should be noted that all marine nuclear plants have been steam plants, a situation that is unlikely to change in the near future.

24.5.2 Particular Requirements of LNG Ships

Apart from cargo machinery, which is discussed separately, the machinery of LNG ships differs from that of other steam ships principally in the boil-off gas supply system for the boilers. The boilers are dual-fuel boilers, capable of operation on residual fuel oil alone, or on a combination of gas and oil. Early practice required that the gas never be burned without oil, which served as pilot fuel to ensure continuity of combustion, but currently, full gas firing is allowed at sea and, under some circumstances, while maneuvering. Fuel oil is also used to supplement the amount of gas boiled off from the cargo when schedules call for high voyage speeds. When discharging cargo, a quantity of liquefied gas is retained to keep the cargo tanks cold on the ballast voyage, so that boil-off is available at all times. Boiled-off gas can be retained in the cargo tanks for a limited time, as the tank pressure rises toward the relief-valve setting, but normally the boil off is consumed in the boilers. Therefore, a steam-dump line to the main condenser is fitted, to enable boil-off gas to be consumed for steam generation even when the main turbines are stopped. The boilers do not differ in general configuration or dimensions from oil-burning boilers.

Boiled-off gas is drawn from the cargo tanks by compressors driven by steam turbines or electric motors, and compressed to two or three atmospheres, then heated to ambient temperature in steam-to-gas heat exchangers. Compressors and heat exchangers are usually located in a midships deckhouse. The gas then flows to the boilers through a double-walled pipe, usually configured as a gas pipe inside a larger-diameter, thin-walled circular duct. The gas pipe cannot pass through the accommodation, and is usually led to the engine room along the main deck, passing outboard of the accommodation block.

Inside the engine-room, the double-walled pipe carries the gas to closet-like *hoods* at each boiler front, which completely enclose the burners and all of the gas piping and valves. The hoods are open at the bottom, and vented to the weather through ducts to motor-driven exhaust fans. The fans draw a continuous flow of air through the hoods, and also through the connecting annulus of the double-walled pipe. Any gas leaked from the gas pipe or from fittings at the burners will therefore be vented. Gas detectors at the fan intakes will sound alarms and shut off the gas compressors.

An inert-gas generator will be fitted, burning distillate fuel to ensure clean product, for inerting cargo tanks when necessary (normally only during inspection or maintenance cycles), and for inerting void spaces where required. In addition, liquid-nitrogen storage or a nitrogen generator will be fitted for purging gas piping and for sealing compressor glands.

24.5.3 Particular Requirements of Coal-fired Ships

Coal-fired steamships differ from oil-fired steamships because of the volume and deadweight penalties of the coal-storage and coal-transfer systems, the larger boilers, and the increased size and number of auxiliary systems (5).

24.5.3.1 Coal storage and transfer systems

Current-technology coal-transfer systems are pneumatic. The coal is loaded from shore into hopper-bottomed bunkers; at the bottom of each hopper is a rotating valve, which allows clusters of coal to fall into a pipe carrying a stream of compressed air. The air stream carries the coal horizontally or vertically as required. Coal is usually transferred daily to day bunkers above the furnaces, to which it flows by gravity.

The size of coalbunkers is large relative to oil tanks, mostly because of the lower heating value of the coal, and also because the plant efficiency is lower. To facilitate filling, the storage bunkers are best concentrated in a single location. The bunkers are elevated above the double bottom to accommodate the hopper bottoms and the transfer system. If placed amidships, the bunkers will have less effect on the trim of the ship as coal is consumed, but will divide the cargo capacity of the ship; if the bunkers are placed aft, transfer is simplified.

24.5.3.2 Boilers

Current-technology boilers are spreader-stoker fired, traveling-chain grate types. These boilers occupy five to eight times the volume of oil-fired boilers of similar steam-generating capacity. Each boiler requires multiple fans fr air supply. Exhaust is through large-volume, stationary-cyclone particle separators and induced-draft fans. Electrostatic precipitators could be added at the separator outlets if necessary, adding to the volume. The boiler efficiencies are four to six percent less than oil-fired boiler efficiencies.

Fluidized-bed boilers are likely alternatives, offering lower overall volumes and higher boiler efficiencies. If fitted with a limestone beds and limestone storage, washing, and circulation systems, emission control is inherent. The technology is well established ashore.

24.5.3.3 Auxiliary machinery

The high-capacity air compressors used for coal and ash handling, and the multiple forced- and induced-draft fans all impose an electrical load 2 or 2.5 times that of oil-fired steam plants of similar output, requiring a correspondingly larger electrical generating plant.

24.6 CONSTRUCTION CONSIDERATIONS

24.6.1 Planning for Production

Modem ships are generally built in accord with the principles of production planning, which require that the ship, including machinery spaces, be assembled of pre-outfitted blocks that integrate structure with machinery and other outfit. The overriding goal in production planning is an increase in productivity. The advantages of production planning are well established and are described in detail in references 6 and 7. Properly executed, production planning results in ships that are better built than they would otherwise be, with machinery that is likely to be more carefully arranged, installed, and commissioned. However, the future operability of a vessel must not be adversely affected by productivity improvements. Some considerations are:

- adequate space for access in service for operation, maintenance, and repair must be provided, even though the intent may be to fit equipment into standard-sized modules,
- where machinery and connecting subsystems are preassembled into modules by a manufacturer, care must be taken to ensure that the module maintains the principles of system integration. For example, services for the module (such as cooling water) should be provided from central sources. The introduction of auxiliaries or fittings of performance similar to, but of different manufacture from other equipment to be provided, should be controlled to avoid a proliferation of equipment that will complicate logistics in service, and
- machinery is most obviously grouped by system and type to simplify construction and normal operation. However, contingency operation, for example, to enable equipment of one system to stand by for similar equipment of another system, or to facilitate recovery from flooding or fire, may require like machinery items serving a single system to be separately located.

24.6.2 Foundations

The discussion in these paragraphs is limited to foundations for propulsion machinery. Foundations for auxiliary equipment and other machinery do not usually affect ship design or construction.

24.6.2.1 Rigid mounting

Most machinery is rigidly mounted. Figure 24.10 is a transverse section through the foundation of a rigidly mounted medium-speed diesel engine. The foundation consists of longitudinal and transverse members, fully integrated into the bottom structure, which support a horizontal seating flange. The mounting flange of the engine is bolted to the seating flange through chocking, which provides solid contact between the flanges. Traditional chocking consists of a series of individual cast iron or steel chocks, each spanning two hold-down bolts, which are individually machined to precisely fit each location after the unit is aligned on temporary supports. Alternatively, continuous chocking may be formed of an epoxy resin, which is poured in place after the unit is aligned on temporary supports, and which then hardens, after which the hold-down bolts are tightened.

For most machinery, fitted bolts, dowels, or keys are used to positively secure one end only, while other bolts have clearances to accommodate thermal expansion. To maintain transverse alignment of diesel engines and other machinery as required, side stops, visible in Figure 24.10, are welded to the seating flange of the foundation, along each side of the engine, but clear of the engine to permit the insertion of tapered keys. When the engine has been aligned, the keys are tack-welded to the stops.

24.6.2.2 Resilient mounting

Resilient mounting is used when necessary, to reduce the structure-borne vibration or noise which the mounted machinery would transmit to the hull. Common candidates include medium- and high-speed diesel engines and gas turbines, and complete generator sets. In principle, resilient mounting substitutes a flexible material or device for solid chocking. Resilient mounting is feasible only where the unit to be mounted is, by itself, sufficiently rigid in bending and torsion. This rigidity is usually present with medium- and high-speed diesel engines (but not low-speed engines) when they are mounted alone, but for complete generator sets, and for gas turbines; the units are first mounted on a stiff base plate, which proves the necessary rigidity. The base plate is then mounted to the hull through the resilient mop'nts. A resilient mount may consist of upper and lower steel or cast iron plates that are separated by a resilient element, comprised of springs or elastomeric material. The upper plate is bolted to the engine or base plate, and the lower one to the foundation. Alternatively, the resilient mounting may comprise an elastomeric material in sheet form that is cut to fit the contact area between the engine or base plate and the foundation. Resilient mounts are loaded principally in compression. Extreme motions, such as those caused by ship motions, are limited in all directions by solid stops.

24.6.2.3 Diesel engines

A foundation for a diesel engine must be sufficiently stiff to absorb forces and moments generated by the engine, while precluding the transfer of bending moments from the hull to the engine. Low-speed propulsion engines are normally seated on the upper flanges of a rigid box girder that is formed as an integral part of the double-bottom structure, such as shown in Figure 24.10. Figure 24.11 shows typical medium-speed diesel examples of engine foundations, viewed in transverse section. The seating flanges for low-speed engines are usually insert plates in the tank top; flanges for medium- and high-speed engines are usually elevated above the tank top, and for geared installations, are usually integral with the foundations of the gearing and pro-

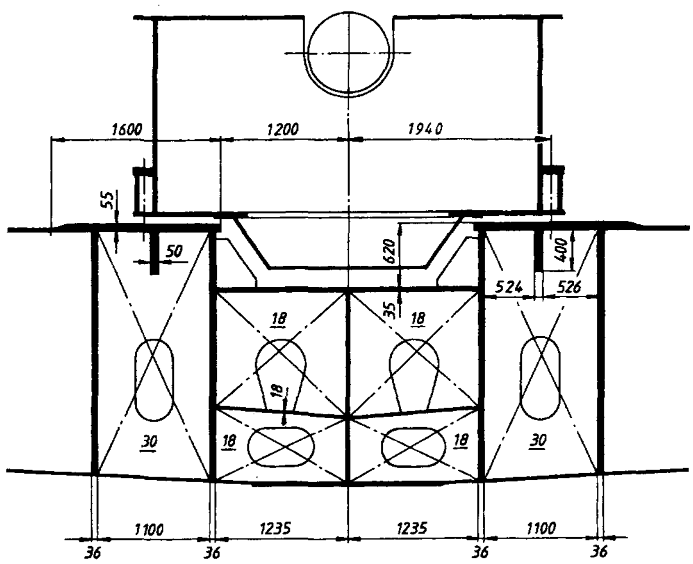

Figure 24.10 Typical Low-speed Diesel Engine Foundation

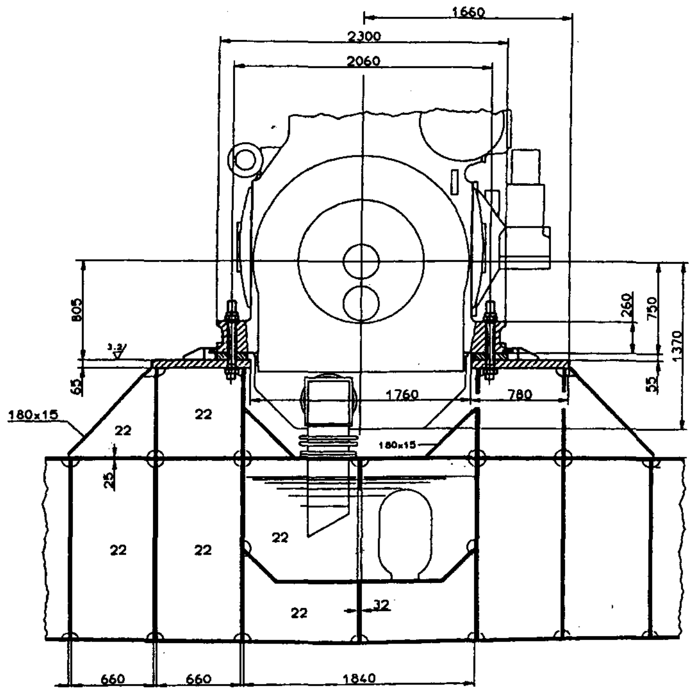

Figure 24.11 Typical Medium-speed Engine Foundation

peller thrust bearing, as in Figure 24.2. Low-speed direct-connected engines, with the main thrust bearing built into the engine bedplate, transmit this thrust to the foundation through fitted bolts, brackets, or end stops.

All low-speed engines are rigidly mounted. Medium- and high-speed engines can be mounted resiliently when circumstances warrant.

24.6.2.4 Gearing

Reduction gearing must be supported in isolation from bending and twisting of the hull. To obtain the necessary rigidity, deep longitudinal and transverse members are used, fully integrated with the hull structure. The main-thrust bearing may be independent or incorporated in the gear case. When the thrust bearing is independent but adjacent to the gear case, the thrust foundation is usually integrated with the gear foundation. Although naval vessels often have resiliently mounted gearing to reduce noise transmission and to provide shock protection, in merchant-ship practice gearing is generally rigidly mounted.

Casings of smaller gear sets may completely enclose the gearing, and are best supported from mountings close to the horizontal centerline through the bull-gear bearings.

Casings of larger gear sets generally terminate in mounting flanges below the bearing housings of the bull gear. In either case the foundation must rise above the tank top to provide a seating surface for the mounting flange on the gear case. As long as it is properly supported, the structure of the gear case can usually be assumed to be sufficiently rigid to maintain alignment of the pinions in mesh with the bull gear and, of gears and pinions upstream of these.

Shims rather than chocks are fitted at the mounting bolts to achieve alignment. Resilient mounts are not used in merchant ships. Turbine shafts are attached to their pi~ons by flexible couplings that, however, can absorb only limited alignment discrepancies.

24.6.2.5 Steam turbines

Foundations for geared steam turbines that are arranged in the typical multi-plane layout, with the condenser below the turbines, are shown in Figure 24.12. A partial transverse bulkhead is located forward of the condenser to support the forward ends of both turbines. The aft end of the high-pressure turbine is most often supported from the gear case, often using longitudinal girders to bridge the span to the partial bulkhead. The aft end of the low-pressure turbine is usually supported by pedestals or a by a second partial bulkhead, aft of the condenser. The after footing of each turbine casing is fixed in position with dowels, keys, or fitted bolts, while the forward footing mounts through slotted holes or includes other provision for thermal expansion.

Shims rather than chocks are fitted at the mounting bolts to achieve alignment. Resilient mounts are not used in merchant ships. Turbine shafts are attached to their pinions by flexible couplings that, however, can absorb only limited alignment discrepancies.

24.6.2.6 Gas turbines

Gas turbines are normally mounted at the factory to a stiff steel base plate in a manner that will allow thermal expansion. The base plate is in turn mounted to the foundation rigidly or resiliently, as called for by circumstances or by turbine manufacturer's recommendations. The turbine foundation may be integrated with that of the gearing, elevated above the tank top as for medium-speed diesel engines (Figure 24.11). Where multi-plane gearing requires an elevated turbine position, the lightweight of the turbines permits the necessary elevation to be achieved using pedestals or partial bulkheads. In this case, a folded configuration may be used, with the turbines aft of the gearing, and the propeller shafting passing below the turbines.

24.6.3 Alignment

The objective in an alignment procedure is to ensure that when the system is in service, the bearings are properly positioned in all three planes, with each bearing carrying its intended share of the load, so that rotating elements are adequately supported and properly engaged with meshing or connecting elements. For diesel engines this means that when the engine is in service and under load, its crankshaft axis will be straight, with almost uniform bearing loads; for gearing it means that in service and under load, the bull-gear bearings will be carrying almost equal loads; for propeller shafting, which is normally aligned to a calculated curve intended to reflect the shaft attitude in service, it means that all bearings will be carrying loads close to the design values.

The principle complications in alignment of propulsion machinery are the flexibility of the hull relative to the propeller shafting, the fact that the foundations of gearing and engines contain lubricating-oil drain tanks, which raise the foundations as the oil temperature rises in service, and the fact that the journals run eccentrically in their bearings under load. The shafting alignment itself is complicated by the weight of the propeller that overhangs the after-most bearing, and of the off-center axial load imposed by the propeller thrust. Final alignment of propulsion shafting and machinery would ideally, therefore, be made with the ship afloat in its normal load condition, with all heavy equipment in place, and with the surrounding hull and foundation at service temperatures, so that only the dynamic effects require calculated corrections. This set of conditions is,

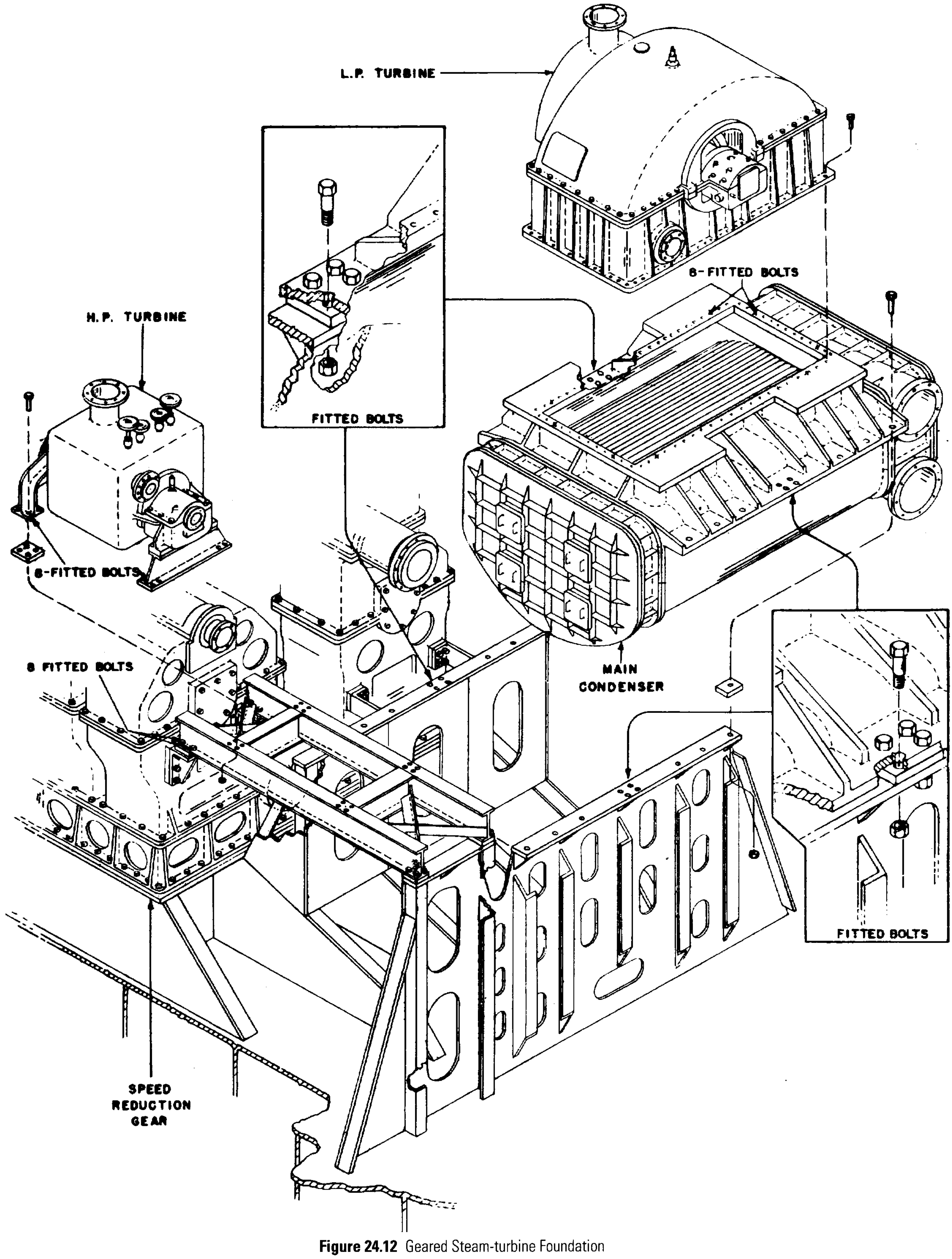

Figure 24.12 Geared Steam-turbine Foundation

however, not often feasible. Practical considerations usually require that the alignment be undertaken in stages, using calculated allowances to account for deviations from service conditions and for deviations resulting from further welding and assembly.

The methods by which alignment is achieved vary, not only between shipyards, but also even from ship to ship, depending on configuration and production schedules. In one likely sequence, the stem tube, struts, line-shaft pedestals, and foundations for the thrust bearing, reduction gear, and engines are installed early in the hull construction period. Because of the weight ofthe propeller, the after-most bearing slopes downward from fore to aft to align to the shaft, an attitude which is achieved by slope-boring the bushing in place, or by aligning a pre-bored bushing to the required slope, and setting it in place with epoxy chocking. Shaft alignment therefore commences before the ship is afloat, with the installation of the stem tube bearings, outboard bearings, stem-tube shaft, outboard shafting, propeller, and shaft seals.

The gear set and engine are installed complete, or erected in place, supported on jackscrews or temporary chocks, as are the line shafting and bearings. The jackscrews or temporary chocks are used to adjust the position of the engine or bull-gear bearings longitudinally, transversely, and vertically until the calculated positions are reached. Preferably, only after the ship is essentially complete and afloat, is final alignment and permanent installation of the shafting, gearing, and engine undertaken. However, if the line shafting is sufficiently long, there is little risk in permanently installing the reduction gear at an early stage, since the length of shafting can be relied upon to provide sufficient flexibility to meet constraints that will then be present at both ends. This flexibility is not present with short shaft lines. The direct-connected diesel engine represents the more difficult ali~nment problem because of the multiple main bearings tEat must be positioned to lie in a straight line and therefore be equally loaded in the service condition.

After the ship is afloat and essentially complete with regard to welding and major weight additions, the line-shaft couplings are made up, usually working forward towards the engine or gear set, usually using gap and sag measurements to check against calculated values, adjusting bearing positions as necessary. When the shafting is complete up to the gear or direct-connected engine, gap and sag are checked, and if necessary, engine or bull-gear bearing positions are adjusted, before this last coupling is made up. With all couplings made up, jacks or strain gages are then used to determine bearing loads, and the calculated cold alignment is achieved, normally by adjusting only the vertical positions of the line-shaft bearings, but, if necessary, the engine or gear bearing heights are adjusted again. When the cold alignment is satisfactory, the line-shaft bearings, and the main-thrust bearing (if independent), the reduction gear, or the direct-connected engine can then be permanently installed: hold-down bolt holes are bored, chocks or shim sets are fitted or resin chocks are poured, hold-down bolts are tightened, and side and end-stops are welded in place.

For geared installations, the turbines or engines are then aligned in a similar fashion: jackscrews or temporary chocks are adjusted to place the turbines or engines in calculated positions, alignment is checked by appropriate methods, and then permanent chocks or shims, with dowels, keys, and hold-down bolts, are installed. See reference 8 for details.

Because of the uncertainties inherent in these procedures, confirmations of the final alignment, after completion and again after trials, are recommended. In practice these confirmations are often limited to checks of gear-tooth contact and to measurement of diesel-engine crankshaft deflections.

24.6.4 Storage During Construction

To facilitate scheduling or because of construction delays, machinery may be delivered to a shipyard well in advance of installation, or may be installed long before commissioning. Machinery must be protected from deterioration during these storage periods. The deterioration may be caused by corrosion, by extreme heat or cold, by infiltration by dust, blasting grit, organisms, or animals, by vibration from nearby machinery, or by pilferage. Much of the deterioration can be avoided if the machinery can be stored in climate-controlled warehouses, but in many cases, it will be stored in open sheds or yards. Reference 9 contains procedures for boilers in particular, which can be applied as well to other components.

Depending on the type of machinery involved, and on the storage conditions anticipated, machinery internals might be protected with desiccants or by charging with nitrogen, or with oil, grease, or other corrosion-inhibiting coatings. In any event, openings and connections are plugged or capped. External surfaces should be primed or painted, and even large items might be wrapped with plastic. Manufacturers can prepare machinery for storage if the storage period is anticipated. However, such preparation, which may involve additional cost and can interfere with installation and commissioning, is not always advantageous to all of the parties involved, and may be avoided even when in the long-term interest of the ship owner.

Once machinery has arrived at the shipyard, and especially after it has been installed, protection may be more difficult. Some machinery can be protected by arranging fans and ducts to circulate air through dehumidifiers in closed circuit, or by dehumidifying whole spaces after sealing them. Limited protection can be provided by strategically placed heaters, by closing openings, and by covering equipment with tarpaulins or plastic sheets.

24.6.5 Testing and Commissioning

Testing and commissioning of all equipment follows a carefully developed plan of procedures and scheduling. Detailed guidance can be found in references 10 and 11.

Most machinery, but not all, is tested by the manufacturer prior to shipping, with instrumentation calibrated, and control equipment and safety devices set and tested. Diesel engines and generating sets are likely to be tested up to full load, as may be some pumps and other auxiliaries, but propulsion turbines and reduction gears are likely to be shop tested without load. These shop tests are generally intended to check assembly and manufacturing, rather than performance. Nevertheless, useful baseline data, such as vibration signatures, can be collected.

As equipment is installed and systems are completed, preparation begins for initial testing. Procedures are different for each system but in general, systems are rigorously inspected inside and out, piping and wiring connections are checked, and tanks, piping, and other components are thoroughly cleaned internally. Boilers are boiled out with an alkaline solution. (Like any other components subjected to chemical cleaning, they must then be neutralized and flushed repeatedly.) Systems are pressure tested and flushed or blown through. Flushing procedures for the more critical systems, in particular lubricating-oil systems and hydraulic systems, are necessarily elaborate, with recirculation loops, temporary strainers fitted at key points, and bearings and other sensitive components initially bypassed. Machinery is styted and safety devices and control equipment are tested by demonstration. Instrumentation is verified at one or more operating values. Automation is set and tested to whatever extent is feasible. All equipment within each system is operated up to the limits imposed by the prevailing circumstances of continuing construction, to prove that it functions as intended.

Once machinery has been commissioned it must be treated, as it would be in service. Temperatures of idle machinery, fluid levels, chemical treatment, and other parameters must be maintained at levels that will prevent deterioration. If equipment is to be idle for periods of days or longer, recommended lay-up procedures should be followed.

When the ship is afloat and all systems are complete, dock or basin trials are undertaken, usually as a final check prior to running the sea trials that follow. Normal and alternative operating procedures are tested, and all equipment, including standby equipment, bypasses, cross-connections, remote and local controls, and safety devices, is checked within practical limits. Although dock trials are conducted mostly in the builder's interests, some machinery can be accepted at that point by the ship owner, thereby alleviating the pressure on owner's representatives during sea trials.

24.6.6 Sea Trials

Sea trials are undertaken to demonstrate the operability and performance of the ship, including all of its machinery, and to gather baseline data for future reference. Detailed guidance can be found in references 11 and 12.

A ship builder may elect to run a preliminary set of builder's trials in advance of the sea trials, as a dress rehearsal. As with the dock trials, if machinery can be tested satisfactorily during builder's trials, it may be to the owner's advantage to accept it as proven.

Sea trials represent the final opportunity before the ship is handed over to the owner to demonstrate that the equipment and systems, as installed and prepared, will operate as intended. Therefore, except for machinery already accepted, and except for machinery which must be tested subsequently, all equipment is operated under observation for sufficient time to demonstrate that it can achieve and sustain intended performance at all levels from no load to overload, under all modes of operation including emergency as well as normal, and under automatic control as well as manual control, and all safety devices are proven.

Machinery that cannot be adequately tested during sea trials might include HVAC equipment, which must await an appropriate climate, and cargo systems on some types of ships, which may have to be tested at the first loading port. For LNG ships and other ships with gas-fueled propulsion plants, trials of the gas-fuel systems might be similarly postponed. Under these circumstances the usual practice is for the owner to accept the ship conditionally, with excepted systems to be proven at the first convenient opportunity.

Diesel propulsion engines of single-engine, single-screw, dry-cargo ships with fixed-pitch propellers cannot normally be tested to rated power when the hull is clean and at ballast draft, even if the engine is run up to its over-speed limit. The usual practice in such cases is to estimate the data for maximum performance of the engine and supporting auxiliaries by extrapolation from the highest levels achieved during the trials, to provide a basis for the owner's acceptance of the vessel.

After sea trials, some machinery is normally required to be opened for internal inspection. A typical inspection list might include propulsion boilers, diesel-engine crankcases, reduction gearing, and main oil sumps, as well as oil filters and strainers. Reduction gears are opened to check tooth contact, and main-engine crankshaft deflections are measured as checks on shaft alignment. Usually, one or more cylinders of diesel propulsion engines will be disassembled for inspection of wear patterns.

Problems revealed during sea trials or post-trial inspections may require immediate rectification before the ship is handed over, or the owner may accept the ship conditionally, with repairs to be completed subsequently.

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CHAPTER 25

The Shipbuilding Process

Mark H. Spicknall

25.1 INTRODUCTION

In order to clearly understand the shipbuilding process, it is instructive to first examine where ship production fits in the context of the range of possible overall production approaches, and why. This is done by examining the product characteristics that dictate the overall production approach for any type of product, and then comparing ships and shipyards along these dimensions to some other products and their production systems, respectively.

From this discussion the production approaches appropriate for different shipbuilding scenarios become apparent. Key product, product structure, and production system characteristics are identified for each scenario, and key operations planning and management principles are also discussed. For the predominate Group Technology-blsed shipbuilding approach, additional discussion of operations planning and management practices is provided. Finally, capacity and inventory strategy is discussed in the context of lean manufacturing principles and aggregate production planning practices.

Although much of this material will be covered in the context of commercial shipbuilding, the vast majority of this information applies to both commercial and military shipbuilding.

Also, this chapter focuses on the overall process and principles of shipbuilding and shipyard operations management. Specific production facilities, processes, and tools within a shipyard are described in the next chapter. Therefore, the reader may find it helpful in reading this chapter to refer to Chapter 26 when more detailed information is desired related to specific types of shipbuilding facilities, process lanes, work cells, or tools.

25.2 GENERAL PRODUCTION APPROACHES

25.2.1 Comparison of Products Based on Attributes Related to Production

This section examines the ship production process in the context of the range of possible production approaches- from low-volume custom and job shop production to continuous- flow manufacturing-in order to make it clear when and why particular production approaches are appropriate for building ships.

Following are key production system characteristics that dictate what type of overall production approach is most appropriate for any type of product:

- product demand,
- demand variability and predictability,
- product complexity,
- product mobility,
- material types and associated joining technologies,
- product variety within a single production system, and
- degree of customizationlvariation among products of any single type.

25.2.1.1 Demand and its variability and predictability

Commercial shipbuilding demand is currently relatively high, resulting in an average production rate for commercial shipyards of about ten ships per year. A few of the most cost-competitive and largest commercial shipyards are producing up to 40 ships per year. Short-term demand variability for any given yard is usually moderate and fairly predictable. However, medium- and long-term demand variability can be substantial and unpredictable.

This type of demand variability is also common for other types of complex industrial capital goods like factories and commercial aircraft. This dictates that production systems for these types of products, including most shipyards, must allow for significant expansion and contraction of overall capacity in the medium-term.

25.2.1.2 Product complexity, mobility, and material type

Even the simplest ships are large and complex products. The primary hull structure of a ship is most often steel and/or aluminum. Welding technology allows for the modularization of this primary structure, which, in turn, facilitates parallel structural assembly work and easier systems installation prior to the final assembly of the primary structure. This early installation of ship system components is commonly referred to as pre-outfitting.

A ship is mobile when it is completed. This allows a ship to be built in a facility with permanent large-scale shops, tools, material handling systems, and services that are dedicated to specific stages of production and types of work, that support very large-scale modularization, and that facilitate efficient material flow. The ability to build modularly within dedicated large-scale facilities results in many dependent stages of assembly and a deep product structure. The associated work breakdown structure shows the work tasks and their dependencies through the many stages of production. This is often called a "product work breakdown structure" or PWBS within the shipbuilding industry (1).

Shipbuilding and large commercial aircraft manufaj.luring are quite similar with regard to the use of these types of production facilities and modular production approaches. This is reflected in the fact that that these two industries have a similar level of capital intensity, with these industries in the U.S. utilizing between $0.35 and $0.45 worth of fixed capital assets to generate $l of value added per year (2).

Office buildings and factories are also very large and complex products. But buildings and factories are not mobile-they must be built in place. This single fact has major implications for the associated production system and approach. If the final product cannot move, the production system must be mobile and temporary, and its use will be limited to only one product/project at a time. This necessarily limits the scale and specialization of production facilities, tools, material handling equipment, and support systems. This, in turn, greatly limits the scale and degree of possible subassembly, modularization, and early systems installation on-site. Substantial subassembly and modularization can be done off site. But the size and weight of these subassemblies and modules are still constrained to what can be transported over the road and/or lifted by limited-capacity mobile cranes at the construction site. These limitations on the extent of possible subassembly, modularization, and early systems installation are reflected in a relatively broad and flat product structure.

Within the domain of production operations management, the term most associated with this type of production is *construction.* In construction, much of the primary structure is erected piece-by-piece or from small sub-assemblies, and much of the systems installation work must be carried out on and within this erected structure. Post-erection systems installation work is often hindered by poor work access and working position. Also, in support of post-erection work within the structure, substantial effort is required for installation and removal of temporary production support servIces.

The commercial building and factory construction industry in the U.S. utilizes between $0.15 and $0.20 worth of fixed capital assets to generate $1 of value added per year-less than half the capital intensity of the U.S. shipbuilding and commercial aircraft manufacturing industries. Not surprisingly, labor productivity in construction environments is less than half that of world-class shipyards and commercial aircraft manufacturers-$65-75 000 versus $130-180000 value added per employee per year (2).

Value Added is defined as follows:

- *Manufacturing industries-Value of Shipments* (sales) minus *Cost of Materials,* and
- *Construction industries-Net Value of Construction* minus *Cost of Materials, Components, Supplies, and Fuels* ..

For *Manufacturing* industries, subcontracting is included in *Cost of Materials.* For *Construction* industries subcontracting is subtracted from *Value of Construction Work* (sales) to obtain *Net Value of Construction.* All italicized terms are as defined by the U.S. Commerce Department, Census Bureau.

The construction-oriented production approach reflects traditional or pre-WWIl shipbuilding, when ships were built virtually piece-by-piece, and system-by-system according to a system-oriented work breakdown structure or SWBS. There are still some unique circumstances when a construction-oriented approach is appropriate for building complex marine systems-these will be discussed later in the chapter. But for the reasons just described, most modem shipyards are capitally intensive facilities that utilize a large-scale modularized approach to production, similar to that used for the manufacture of other mobile and complex engineered products.

25.2.1.3 Product variety and degree of customization/ variation between similar products

Some shipyards specialize by product type while others produce a variety of ship types simultaneously. It is not unusual to see crude oil tankers, product tankers, LNG and LPG tankers, and container ships being built all at the same time in some of the world's most competitive commercial shipyards. It is also fairly common to see commercial and military ships being built simultaneously in shipyards in the U.S. and overseas.

Some substantial variability is also common between ships of the same type and size being built in the same shipyard. For military ships, technology upgrades from ship to ship of a class are very common. Technology is evolving ever more rapidly, and the military wants the latest technology available as early as possible.

A myth exists in some circles that the commercial shipbuilding market consists primarily of large series of standard ships.

Those seriously involved in the commercial shipbuilding business know this not to be true, but lets look at some hard evidence. Figure 25.1 shows the number of commercial ships contracted in large and medium-size Japanese shipyards between 1998 and 2000 by the number of ships in standard series. A standard series could consist of ships within a single contract or ships from multiple contracts and owners. This data shows that one third of the ships contracted during that period were unique one-offs. Over 76% were part of a series of four or fewer ships. Less than 15% of the total ships contracted during that period were part of series of seven or greater with the largest series of standard ships being twelve (3).

Also, during a trip to the Samsung and Hyundai shipyards in early 2002, the author asked shipyard managers and shipowners about the degree to which owners request changes from standard designs. It was found that owners often provide their own designs. When standard shipyard designs are used as a baseline, significant changes are almost always made to outfitting specifications, often to steel specifications, and sometimes to principal dimensions. These shipyards highlighted the fact that they consider their ability to give owners exactly what they want to be a major competitive advantage.

So at a minimum, a typical shipyard must be able to deal with some significant degree of variation among ships of a type, and could very well also require the flexibility necessary to handle multiple product types.

This contrasts with the typical commercial aircraft production system. Commercial aircraft manufacturers also produce a variety of products. But this variety is limited. Each product type is designed in-house, and though there is some variation within each product type, potential work content variability is limited to less than 15% on average (4) by a limited set of potential options. There is typically enough volume of each product type to justify the creation of specialized production facilities for each. So a typical aircraft production facility would be configured to produce one product type with some limited degree of potential variation between individual products.

On the other hand, building and factory construction is similar to shipbuilding along the dimensions of product variety and variation. Most commercial construction companies build a variety of products. And the vast majority of

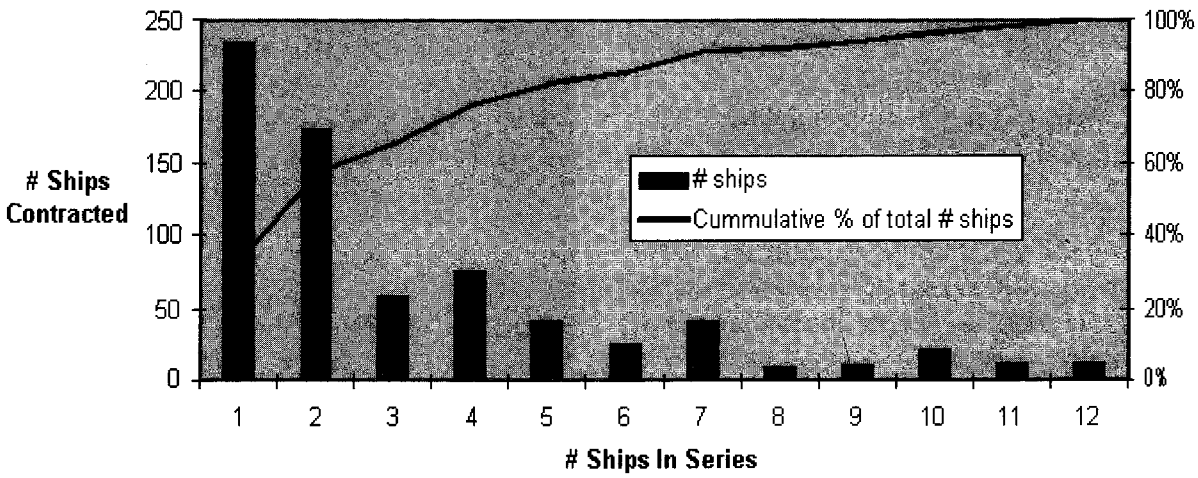

Figure 25.1 Number of Ships Contracted Per Number of Ships in Series, Japan 1998–2000

large-scale buildings and factories are truly custom products. Even among construction products of the same type there is typically a significant degree of variation. An owner typically has a unique design created by an architectural firm and then contracts a construction company to build it.

25.3 SHIP PRODUCTION APPROACHES

The deep product structure of a typical ship is similar to that of a commercial aircraft, reflecting many stages of subassembly, modularization, and pre-outfitting. This contrasts with the relatively flat product structure of a typical stick-built building or factory. Also, the capital intensity of a typical shipyard is similar to that of a typical commercial aircraft manufacturing facility, and much higher than that of a commercial building or factory construction system. Yet the product variety and variability within shipbuilding is much closer to that of commercial building and factory construction.

So what type of production strategy or approach is most appropriate for shipbuilding? The answer to this question is dependent primarily on production volume and variability. At one extreme of the shipbuilding industry, a few shipbuilders are building highly customized products, one or a very few at a time. At the other extreme, a few shipyards are building only standard ships of a single type in large numbers. But the substantial majority of shipyards are building some significant number of ships simultaneously with some variety in ship type and some significant variation among products of each type. These three different situations require somewhat different production approaches.

25.3.1 Marine Product Construction

The important factors that dictate the use of a construction-oriented strategy in a marine context are that product-to-product variation is very great, and only one or a few of each will be built. So a substantial capital investment in a permanent production system that can handle even somewhat similar products cannot be justified.

Because of the great similarity of this work to commercial building and factory construction, many commercial construction companies also do work in marine construction. In the marine domain the construction approach is most prevalent in the production of complex offshore systems such as the semisubmersible *Crazy Horse* shown in Figure 25.2 and the *Balal* platform shown in Figure 25.3.

Complex marine systems construction is carried out in essentially the same way as commercial building and factory construction and pre-WW II shipbuilding. A production site is identified that is large enough for the project, that

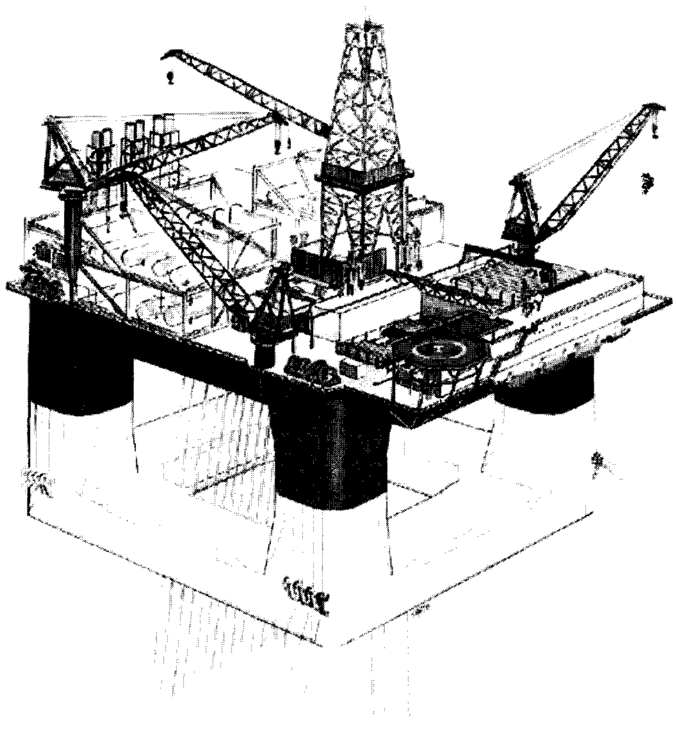

Figure 25.2 Semisubmersible *Crazy Horse*

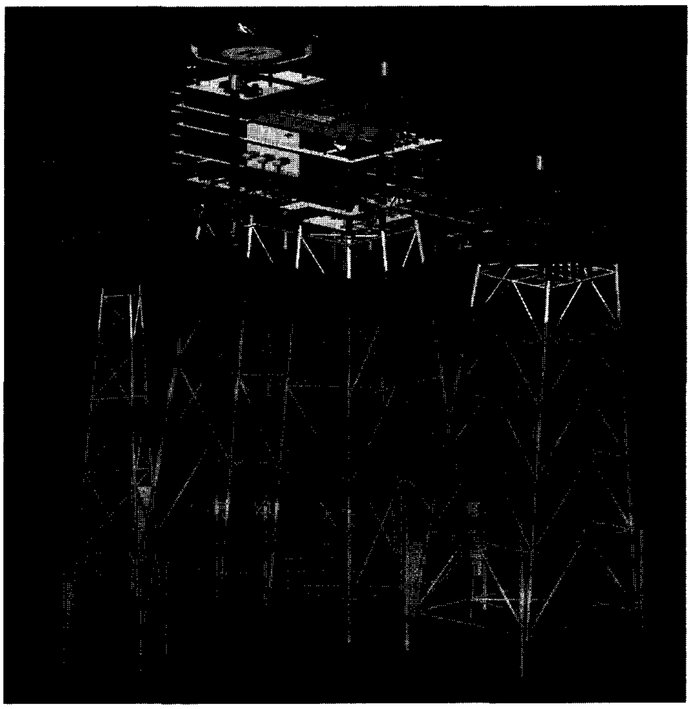

Figure 25.3 *Balal* Platform

allows for launching the product, and that is reasonably close to the product's required destination. A temporary production system is defined and put into place.

Construction tasks and their interdependencies are defined, and the resulting task network is used as the basis for project scheduling using critical path methods (CPM) and project management. Production operations management for construction is entirely project-oriented because the production system is focused on a single project. There are numerous references available on construction management and CPM (5-7). The predominate network scheduling tools utilized for project management are Primavera and Artemis, but there are many others available, as well.

As described earlier, the primary structure is built mostly piece-by-piece or from small subassemblies with relatively little structural modularization. System/outfit modules and components are installed on and within the structure as it is erected, and are constrained in size and weight to what can be handled by limited facilities and mobile cranes at the site.

Tools are positioned around the final assembly site as space allows, minimizing to the greatest extent possible the distance that parts and subassemblies must be moved for final installation on and within the erected structure. When and where subassembly is done, the associated tools are laid out to provide as logical a material flow as possible given the constraints of the construction site.

Mobile cranes with 75 tons of lifting capacity or less are most common on ship and offshore construction sites, although larger cranes are used occasionally. It is also sometimes possible to utilize floating cranes with thousands of tons oflifting capacity. Figure 25.4 shows a typical offshore product construction site.

After shore-based assembly and some system testing are completed, the product is launched usually by skidding or by flooding a building basin. For a ship or relatively small offshore product built in this manner, in-the-water outfitting and systems testing and trials are then completed and the product is delivered to the customer. For many large offshore structures, shore-based construction is used to complete the largest major assemblies. These assemblies are then towed or transported by barge or heavy lift ship to their operations site where on-site launching, assembly, final outfitting, and testing are completed. Photos and videos showing the construction and the on-site launching and final assembly sequence for an offshore structure are available at http://www.oil-gas.uwa.edu.au/.

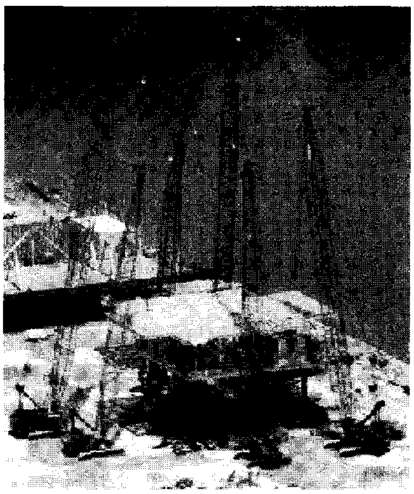

Figure 25.4 Offshore Product Construction

25.3.2 Group Technology-based Ship Production

25.3.2.1 Overview of the group technology-based shipbuilding approach

The vast majority of shipbuilding involves the simultaneous production of multiple products of different types with some significant variation within product types. A key to this type of production is to recognize that even given product variety and variation, there is a very high degree of similarity between most ships' intermediate products. Intermediate products are the sub-products that are produced and then concatenated through multiple production stages to create a final product.

For example, even though a shipyard might be simultaneously building tankers, bulkers, and container ships, each of these ship types have major structure made up of stiffened steel panels that are quite similar in terms of the processes that are required for their production.

Another key is to.recognize that even though the volume of ships being built simultaneously might be relatively low as compared to the production volume of other industries, in most cases the volume of similar intermediate products is substantial. For example, if a yard is concurrently building only a handful of ships at any given time, it might have a fairly steady weekly demand for hundreds of similar structural stiffeners and pipe spools, and dozens of similar plate parts and stiffened structural panels.

These two key factors taken together, similarity and volume of intermediate products, provide the foundation for a Group Technology-based production system. The objective of Group Technology (GT) is to exploit the similarities of intermediate products to gain production economies of scale for non-standard products even when produced in moderate volume.

Within a GT-based production system, intermediate products of every type and at every level are examined and

Intermediate Product	Process A	Process B	Process C	Process D	Process E	Process F	Process G
1	x		x	x			
2		x		x		x	
3	x				x		
4		x				x	
5				x		x	
6	x		x	x			
7		x				x	
8	x				x		x
9	x		x				
10		x		x			
11	x				x		
12	x		x	x			
13		x		x		x	
14	x						x
15			x	x			
16		x				x	
17	x				x		x
18	x		x				
19					x		x
20		x		x		x	

Figure 25.5 Example Intermediate Products and Associated Production Processes

Intermediate Product	Process A	Process B	Process C	Process D	Process E	Process F	Process G
1	x		x	x			
6	x		x	x			
9	x		x				
12	x		x	x			
15			x	x			
18	x		x				
3	x				x		
8	x				x		x
11	x				x		
14	x						x
17	x				x		x
19					x		x
2		x		x		x	
4		x				x	
5				x		x	
7		x				x	
10		x		x			
13		x		x		x	
16		x				x	
20		x		x		x	

Figure 25.6 Example Intermediate Products Grouped into Production Families

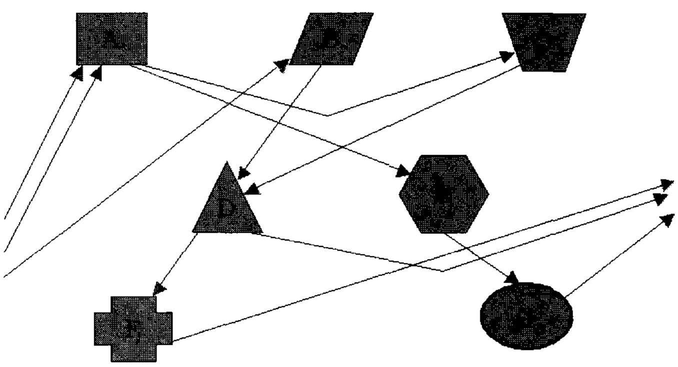

Figure 25.7 Job Shop Layout and Associated Example Intermediate Product Flow

grouped into families based on the physical attributes that dictate their production process (Figures 25.5 and 25.6).

Demand for each intermediate product family is evaluated to determine if the creation of a dedicated process lane or work center can be economically justified. This often results in the reconfiguration of a production system from a job shop layouts to a flow-based layouts (Figures 25.7 and 25.8).

The development of GT-based process lanes and work centers results in facilities, tools, and worker skills that are specialized for the production of specific intermediate product families. Work within each process lane or work cell becomes fairly repetitive, resulting in substantially higher productivity and resource utilization than a traditional or job-shop-oriented production approach. This specialization of work by intermediate product family also creates the opportunity for increased use of semi-automatic and automatic machines and tools, which can improve productivity even more. The following section lists typical shipbuilding GT-based intermediate product families. See the next chapter for descriptions of many of their associated shipbuilding production processes.

25.3.2.2 Typical intermediate products for a GT-based shipbuilding approach

Following is a list of the intermediate product families that are most common to GT-based shipbuilding:

- Structural piece-parts
  - Large parallel parts from plate
    - Flat
    - Simple Shaped
    - Complex Shaped
  - Large non-parallel parts from plate
    - Flat (Figure 25.9)
    - Simple Shaped
    - Complex Shaped (Figure 25.10)
  - Small internal parts from plate
  - Stiffeners from stock structural shapes/profiles
    - Straight (Figure 25.11)
    - Simple Shaped
    - Complex Shaped
  - Built-up stiffeners
    - Straight
    - Simple Shaped
    - Complex Shaped
- Structural subassemblies and sub-blocks made from structural piece-parts
  - Large flat stiffened panels (typically shell, decks, bulkheads, tank tops, double bottoms) (Figure 25.12)
  - Medium-sized flat stiffened panels (typically large webs)

- Large curved stiffened panels (curved shell)
- Small flat stiffened panels (small webs, floors, internal structure) (Figure 25.13)
- Structural outfitting components (simple foundations, supporting framework for outfit units, ladders, etc.)

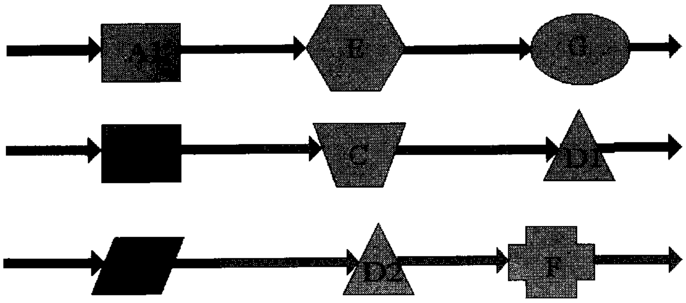

Figure 25.8 Process Lane Layout for Example GT-based Intermediate Product Families

Figure 25.9 Flat Non-Parallel Plate Parts

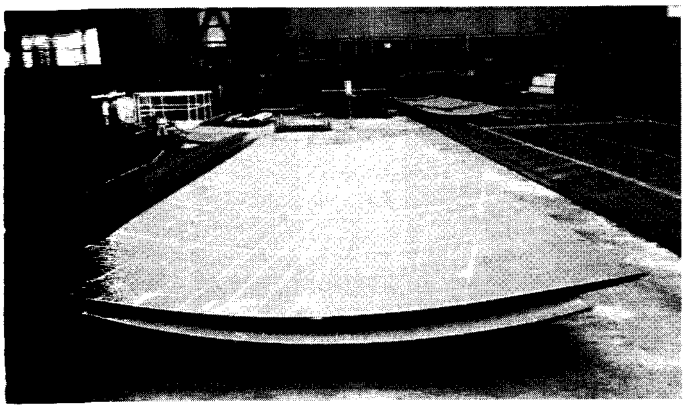

Figure 25.10 Plate Part with Complex Curvature

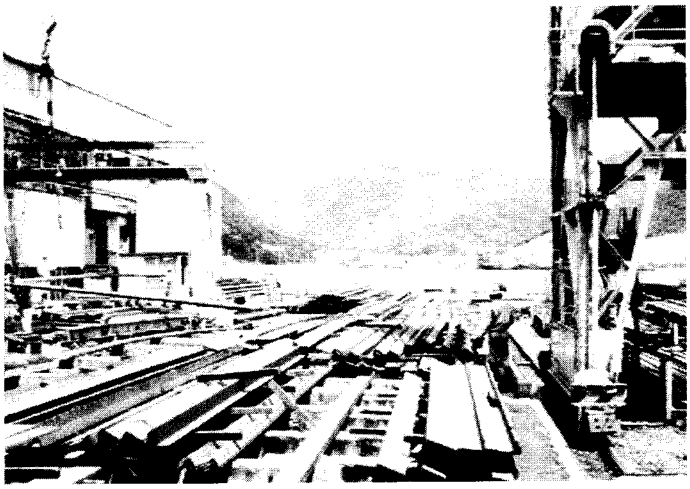

Figure 25.11 Straight Fabricated Stiffeners

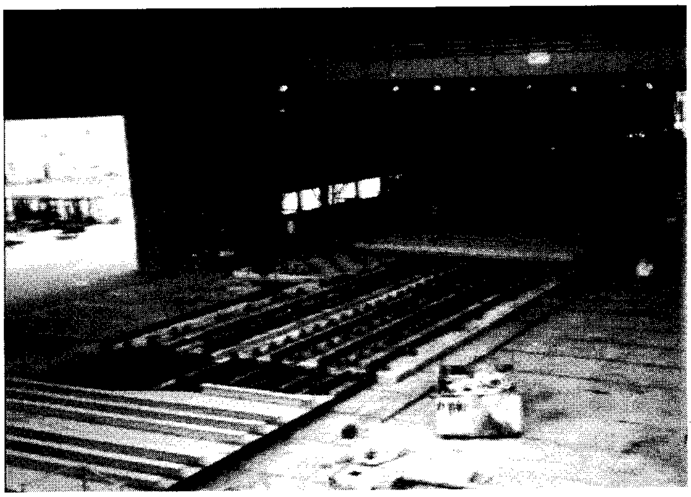

Figure 25.12 Large Stiffened Flat Panels

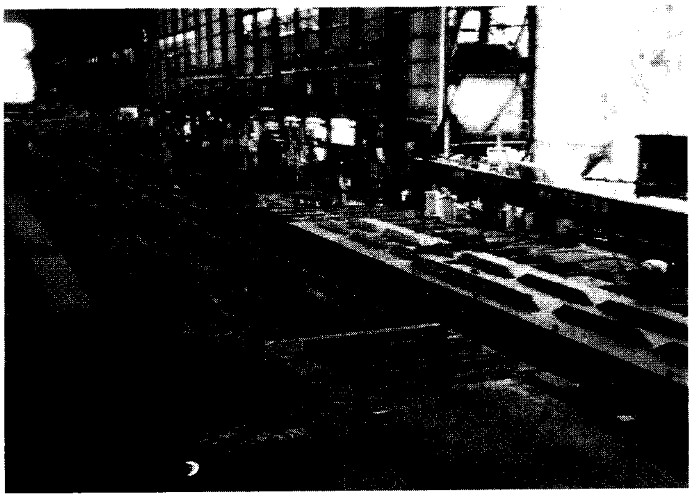

Figure 25.13 Small Stiffened Panels

- Blocks, sometimes called structural units, sections, or modules
  - Flat (Figure 25.14)
    - Open
    - Closed/sandwich
    - Special/irregular (hatch coamings, large foundations, casings, etc.) (Figure 25.15)
  - Curved (Figure 25.16)
    - Open
    - Closed
    - Special/irregular
    - Superstructure
- Outfitting parts and components
  - Pipe spools (Figure 25.17)-classified by material type, size, number and type of bends and end preparations, and surface preparation or coating requirements
  - HVAC ducting spools-classified by size, and number and type of bends
  - Joinery-classified by material type, size, and shape
  - Electrical cables-classified by type and length
  - Pipe hangers-classified by type and size
  - Wireway hangers-classified by type and size
  - Machined components and assemblies-classified by required machining and assembly operations
- Outfit units/assemblies/modules
  - Machinery units
    - Large (Figure 25.18)
    - Small (Figure 25.19)
  - Pipe units (Figure 25.20)
    - Large
    - Small
  - Electrical units
    - Large
    - Small
  - Accommodation units
- *Hot* or *Stage 1* outfitted blocks (blocks with all required welding work completed and any piping and machinery installed that can withstand blasting and painting)-classified by type of outfitting required
- Blasted and painted blocks-classified by type of coating system required, size, and whether open or closed
- Grand blocks (sets of blocks joined together after blast and paint and prior to cold outfitting and erection)
  - Flat
  - Special flat
  - Curved
  - Special curved
  - Superstructure (Figure 25.21)
- *Cold* or *Stage* 2 outfitted blocks and grand blocks (with as much outfitting installed as possible prior to erection)

Figure 25.14 Flat Blocks

Figure 25.15 Large *Special* Foundation Blocks

Figure 25.16 Curved Blocks and Start of Curved Panel

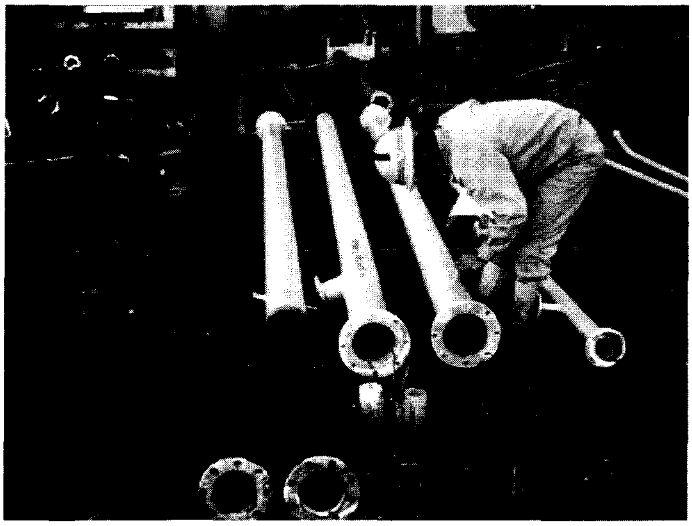

Figure 25.17 Pipe Spools

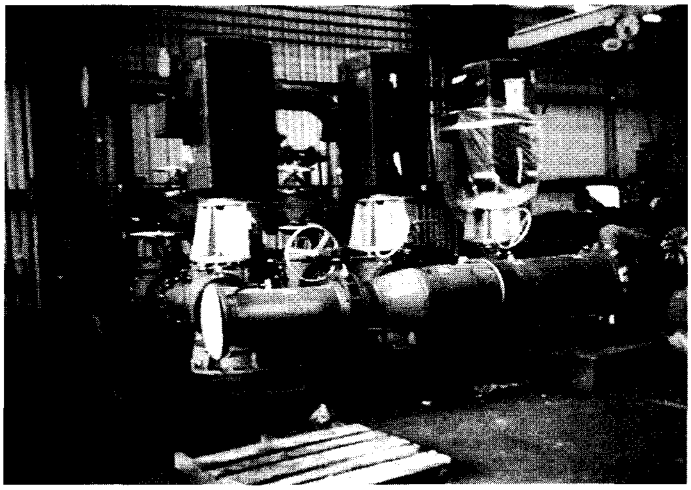

Figure 25.19 Small Machinery Outfit Unit

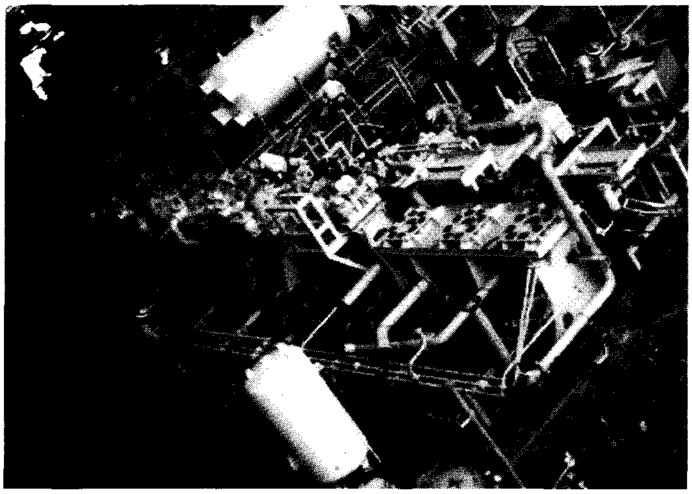

Figure 25.18 Large Machinery Outfit Unit

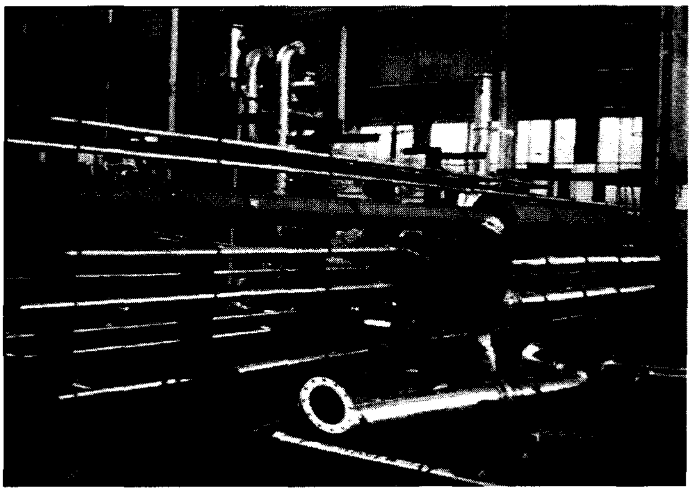

Figure 25.20 Pipe Outfit Unit

(Figures 25.22 and 25.23)-Classified by type of outfitting required

- On-board outfit zones (spaces onboard the ship that enclose discrete and logical sets ofrequired on-board outfitting work)
  - Classified by type of space, which determines the predominate type of outfitting required
    - exterior
    - cargo
    - accommodations
    - machinery
    - electrical (Figure 25.24)
    - tank
- Ship systems (for the system testing stage of production; fuel oil, lube oil, auxiliary power, high pressure air, firefighting, radar, etc.)-classified by type of testing work required
- Integrated systems (for trials stage; propulsion, navigation, etc.)-classified by type of integrated testing work required

The facilities and equipment required for the production of many of these intermediate product families are described in detail in the next chapter. Note that for Stage 2 on-block outfitting and on-board outfitting, the blocks and outfit zones are stationary and specialized work crews move from block to block or from zone to zone based on block or zone outfit classification. In these later stages of outfitting, GT classification serves as the basis for defining and managing these specialized work crews as opposed to work centers or process

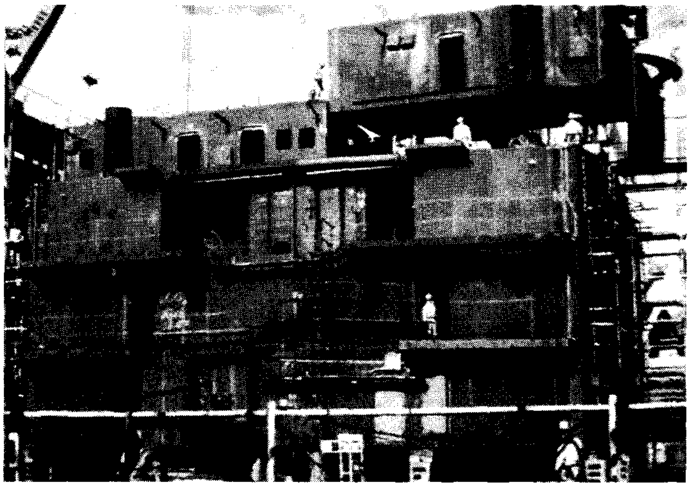

Figure 25.21 Superstructure Grand Block

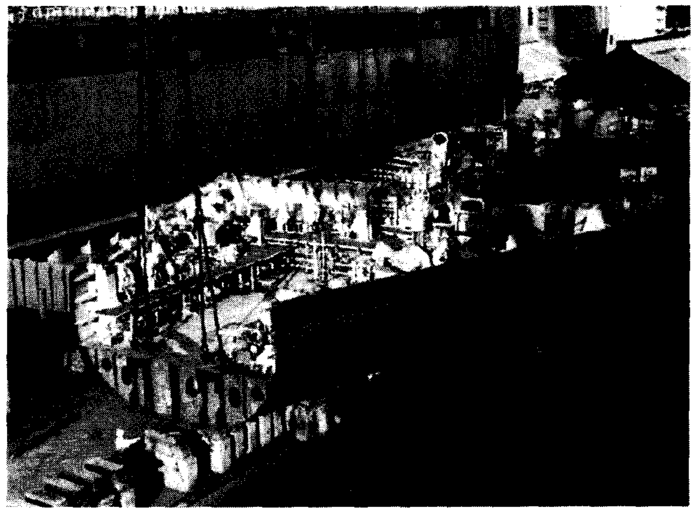

Figure 25.23 Large Outfitted Engine Room Block

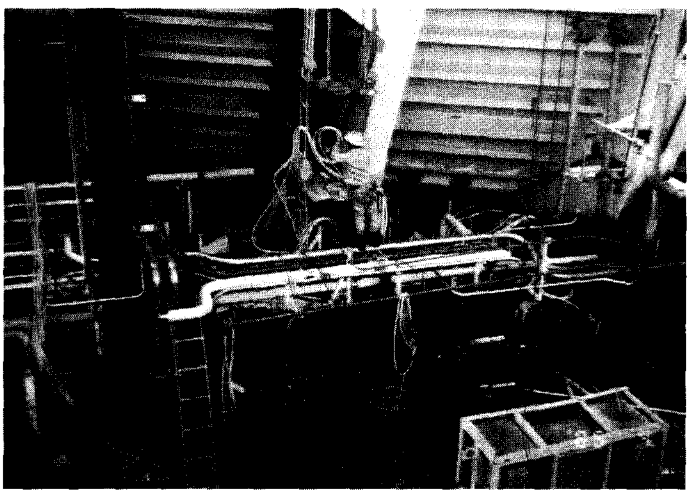

Figure 25.22 Stage 2 On-Block Outfitting

Figure 25.24 On-Board Electrical Outfit Zone

lanes. For example, a work crew specializing in accommodations outfitting would move between accommodation zones as the zones become available for outfitting. Likewise, a work crew specializing in the outfitting of machinery blocks would move from machinery block to machinery block as these blocks become available for Stage 2 outfitting.

25.3.2.3 Typical material flow in group technology-based shipbuilding

Figure 25.25 shows the typical material and work flow within a Group Technology-based shipyard. Primary flows are shown with bold lines. Note that purchased materials and components are installed throughout the production process.

Everything from raw materials such as paint and stock plate, stiffeners, and pipe, to assembled blocks and outfit units, and even completely outfitted deckhouses, can be purchased from commercial suppliers. The cost of purchased materials and intermediate products can account for as much as 70% of the cost of a ship. Production versus purchasing strategy, and supply chain management will be discussed later in this chapter.

Note that while most structural piece parts become part of structural sub-assemblies, some piece-parts are installed during block assembly, grand block assembly, ship erection, and on-board outfitting. Likewise, while most structural subassemblies are used for block assembly, some like foundations are installed during Stage lon-block outfitting and others like small decks and partial bulkheads that cannot be adequately supported within a block might be installed in a grand block or within a zone on the ship.

Most outfit parts and components are installed in outfit units/assemblies or on-block. Some outfit parts and components are installed during on-board outfitting, including make-up pieces for distributive system that cross erection breaks. The largest purchased outfit components such as main engines, gensets, propellers, rudders, and cranes are typically erected on the ship.

25.3.2.4 GT-based shipyard operations management

The key to minimizing the cost and lead-time for individual ships in a GT-based shipyard is to most efficiently and cost effectively utilize production resources across all ships being built at any given time. All planning and scheduling must be based on this aggregate perspective. Key contract dates tied to cash flow are still critical, but the management of individual ships and contracts (project management) is secondary. This operations management approach is very similar to that used in commercial aircraft production and even automobile manufacturing, and is fundamentally different from construction management, which focuses primarily on individual products or projects with their own production resources.

Many shipyards that have evolved from traditional ship construction practices have modified their use of project management/network scheduling tools to suit this aggregate planning approach (7,8). In this regard, most modem network scheduling/project management tools support the use of multi-project networks, the sharing of production resources among multiple projects, and the generation of resource-specific schedules that include all associated tasks independent of contract/project. Other shipyards have implemented material requirements planning (MRP) or manufacturing resources planning (MRP II) systems that essentially accomplish~he same aggregate planning objectives from the perspective of intermediate products rather than tasks. Some shipyards have attempted to integrate these two approaches (9).

One must be careful utilizing an MRP system for the production planning and scheduling of an extremely complex engineered product like a ship, however. There are two reasons for this. First, the number of part numbers for a ship is extremely high compared to that for other products, and some MRP systems may not be able to deal with this level of data management. Second, MRP assumes a purely hierarchical product structure, but the upper levels of a ship's product structure are not purely hierarchical. For example, there can be many-to-many product structure relationships between blocks and on-board outfitting zones-i.e. a single on-board outfitting zone might result from the erection of several blocks, and the erection of a single block might

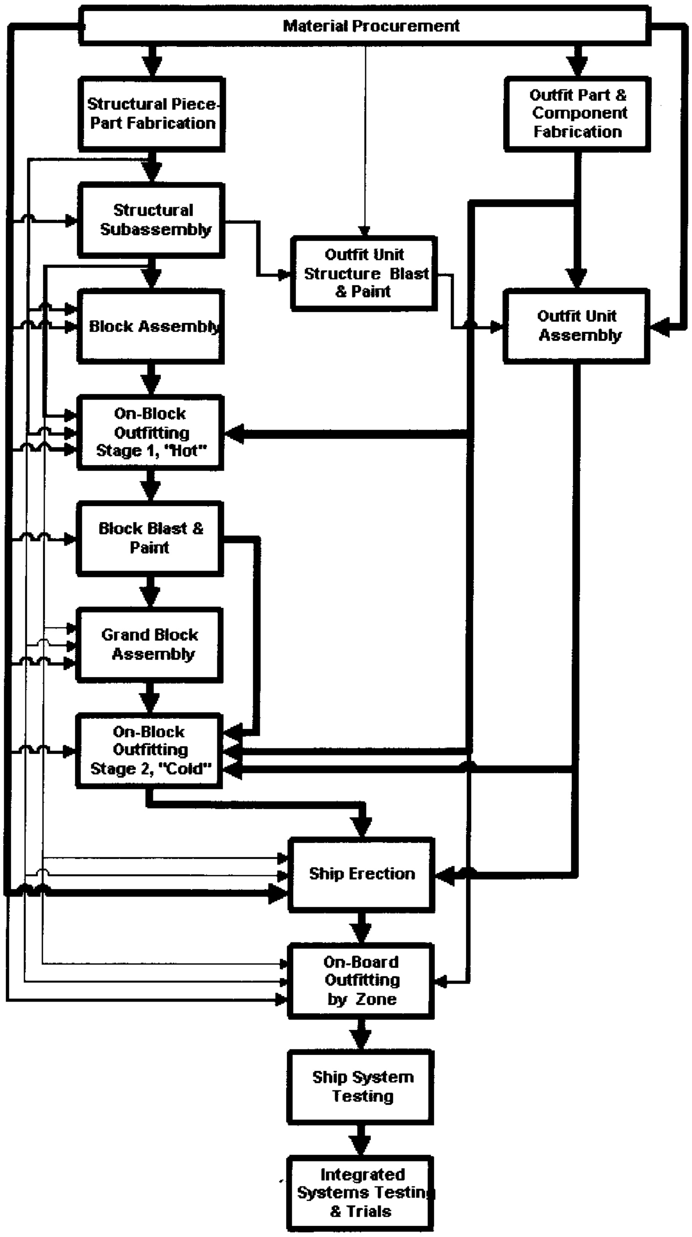

Figure 25.25 Typical Shipyard Material and Work Flow

playa role in the formation of several on-board outfitting zones. Similarly, there can be many-to-many product structure relationships between on-board outfitting zones and ship systems-i.e., a single outfitting zone can contain portions of several ship systems, and a single ship system can pass through several outfitting zones (Figure 25.26).

For planning to be complete and accurate, all of a ship's intermediate products and their interdependencies must be captured. MRP does not support this for a ship above the level of major assembly erection in the product structure, whereas there is no problem capturing these many-to-many

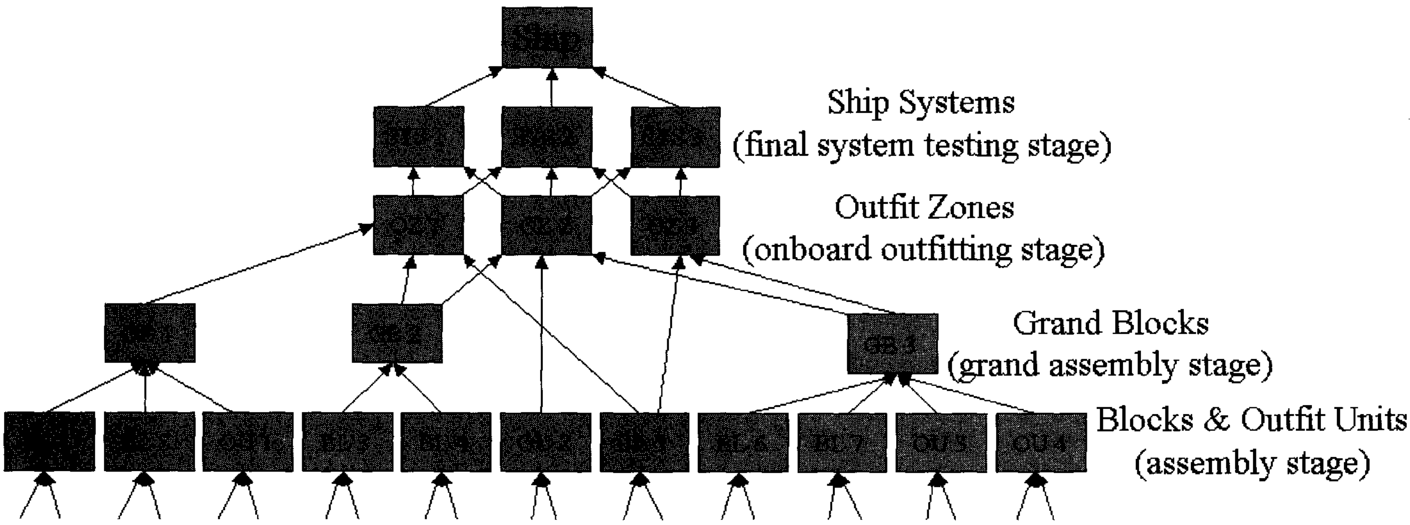

Figure 25.26 Example of Many-To-Many Relationships Within the Upper Levels of a Ship's Product Structure

relationships in the form of a work breakdown in network form within a network scheduling/project management tool.

As in most production operations, capacity and resource planning, and work scheduling are carried out at three levels of detail matching different time horizons:

1. long-range (time horizon extending to at least two times the anticipated life cycle of current products),
2. medium-range (time horizon extending through existing and likely planned work), and
3. short-range (time horizon extending through the end of existing work that is not likely to change in priority and sequence).

The planning units used in long-range planning are ships, and the resources addressed at this stage include those few that have historically been most critical. The planning ~nits most often used for medium range planning include the high level intermediate products (blocks and grand blocks, outfit units, on-board outfit zones, ship systems) that utilize any production resources that might be critical.

All intermediate products are considered in short-range or shop floor planning, with work package definition, sequencing, and scheduling carried out by intermediate-product-specific production resource.

The GT-based shipbuilding environment consists of many interdependent stages of production. Excellent material, process, and quality control are essential for production to flow smoothly from stage to stage.

This control starts with supply chain management. As shipyards and many other industries seek to focus on their core competencies; the amount of purchasing and subcontracting has increased.

Therefore, greater emphasis is being placed on supply chain management. Fundamental to good supply chain management is:

- the establishment oflonger-term relationships with fewer vendors/suppliers based on mutual long-term cost, schedule, quality, and improvement benefits, and
- the rapid and accurate communication of product, demand, and schedule information between customers and vendors/suppliers.

There are various efforts underway to improve supply chain modeling, planning, and integration within the shipbuilding industry (11-14).

Internal material control is also critical. All major shipyards today utilize computer-based material control systems to track material location and status. Bar coding is now common for the identification of intermediate products. Some shipyards have developed and evolved in-house material control systems while others have purchased and adapted commercially available tools.

Critical to internal production process control is control of intermediate product and associated process cost and productivity, and lead and cycle times. Most shipyards have in place cost and cycle time monitoring systems for each work center, process lane, and specialized work team. These systems can be used to continuously track cost and cycle time variance by individual intermediate product, or intermediate product type/work center or team.

Many shipyards also utilize earned value analysis/management, or what is sometimes called a cost-schedule control system, CS^2. Using earned value analysis, the overall budgeted cost of work completed to date for each project is compared to the actual cost of work completed to date and the budgeted cost of work scheduled to date to obtain project cost and schedule variances and projections. Note the project orientation of this approach that might shift focus away from the more important issues of aggregate operations performance. The Project Management Institute is currently documenting standard earned value management practices (15). The U.S. Defense Systems Management College also has available extensive information on the U.S. Defense Department's earned value management practices (16).

Quality control is also critical to GT-based production. If parts and subassemblies do not fit or function properly, rework or replacement is required causing increased material and labor costs and cascading schedule disruption throughout the production system. Statistical quality/process control methods (SQC/SPC) developed in the 1930s (17, 18) have been employed with great success in the shipbuilding industry since the use of GT-based shipbuilding approaches became widespread in Japan in the 1960s (19-31). Every world-class shipyard today has well-established SQC/SPC processes.

25.3.3 Series Production of Standard Ships

There are a few shipyards that produce only standard vessels in large volume. Standard ships will obviously have identical intermediate products. However, GT will still play some significant role in such a production system because, for example, not all flat stiffened parallel panels or straight pipe spools are going to be identical even within a standard ship. However, because of the much greater number of identical intermediate products, this production system will likely be somewhat more tightly integrated than a fully GT-based production system, and will have potentially,greater application of automation because of reduced need t>r production flexibility to accommodate more typical intermediate product attribute variability.

A good example of this type of shipyard is Odense Lindo, as it was configured to build several identical VLCCs in the 1990s. The long parallel mid-body of a VLCC results in many identical structural parts, subassemblies, blocks, and grand blocks. This yard was very highly automated to take advantage of these large numbers of identical structural intermediate products and minimize the impact of high labor rates.

For standard products, planning and scheduling are much less complex. However, production control becomes more critical because the various sequential production processes and stages are more tightly integrated than in a typical shipyard where there is some excess capacity and/or inventory buffers between processes to absorb performance variance resulting from the greater level of intermediate product variability.

25.3.4 Applicability of lean Principles and Aggregate Production Planning to Shipbuilding

There has been a great deal of talk about Lean Shipbuilding over the last few years, particularly in the U.S. (32). Lean is a term coined by a team at MIT to describe the Toyota Production System of the 1980s (33). They state, "The principles of lean production include teamwork, communication, efficient use of resources and elimination of waste, and continuous improvement." In addition, lean production is described to include the following principles and methods:

- collaborative product design,
- production process design and analysis,
- elimination of non-value-added work,
- work standardization,
- demand balancing and resource leveling,
- process control,
- preventative maintenance,
- supplier and employee involvement,
- mistake proofing,
- workplace cleanliness and organization,
- visual communications and controls,
- flexible resources,
- one-piece flow, and
- pull.

Virtually all of these principles and methods predate the concept of lean, and have deep roots in manufacturing, operations management, industrial engineering, and quality management, not to mention common sense. To become a world-class manufacturer, one should, of course, strive to apply such principles and methods in an integrated and sensible manner. Indeed, all world-class shipyards have effectively uses most of these principles and methods for decades to continuously improve performance. Be that as it may, the recent attention given to lean production within the U.S. shipbuilding industry makes it important to examine its core principles and their applicability to ship production.

Lean advocates distinguish lean production as a coordinated use of the principles and methods identified above to continuously strive to minimize waste. There are many kinds of waste in manufacturing, but the pursuit of lean production is ultimately characterized by a focus on reducing inventory and excess production capacity. Therefore, to become lean a manufacturer, one should use the concepts and methods identified above to continuously strive to:

- minimize purchased material and components inventories, work-in-process inventories (WIP), and finished

goods inventories so as to minimize material management and other inventory-related costs, and
- balance capacity and improve process control and quality so as to minimize both idle capacity costs and capacity wasted on rework.

In principle these seem to be reasonable objectives. But is it true for all industries and for all business environments and scenarios that production should continuously strive to reduce excess inventory and production capacity? Let's consider a simple production system example.

A production system has a constant demand rate of 40 products per week. All products to be produced have exactly 4 resource-hour of work content. Process performance for the associated production resource is constant with a work time of exactly 4 hours per product, and each production resource is available and working exactly 40 hours per week.

Given that there is absolutely no variability within this production system, it makes sense to strive for a constant capacity of four production resources operating at 100% utilization (demand for resource-hours = 40 products per week x 4 resource-hours per product = 160 resource-hours per week; number of resource required = 160 resource-hours per week / 40 hours of weekly capacity per resource = 4 resources). Utilization equals demand divided by capacity.

Also, because there is no variability in this production system, there is no fear of product shortages and thus no need for inventory. So in the absence of variability, it makes sense to continuously strive to reduce inventory and excess production capacity.

But what happens if even just a small amount of variability is introduced into this production system? Let's ~ary the demand rate, product work content, resource performance, and resource availability each by only plus or minus 5% and examine the impact on this production system. The demand rate can now vary from 38 to 42 products per week. Product work content can now vary from 3.8 to 4.2 resource-hours. Resource performance can now vary from 0.95 to 1.05 times the product work content. And resource availability can now vary from 38 to 42 hours per week. Note that average demand, work content, resource performance, and resource availability are exactly the same as before.

But now we have an occasional worst-case situation of having to deliver 42 products per week, with these products having 4.2 resource-hours of work content, production resources performing at a rate of 1.05 times work content, and resource availability of only 38 hours per week. How can the production system meet demand during these worst-case occasions?

One approach would be to always have enough capacity ready to deal with this worst-case scenario when it occurs. This would require a capacity of(42 x4.2 x 1.05) / 38 = 4.9 resources. If having a fractional resource is not possible, we must round this up to five required resources. Given that average demand, work content, resource performance, and resource availability are exactly the same as before, this results in an average resource utilization of 80% (160 resource-hours per week average demand and 200 resource hours per week capacity). So maintaining excess capacity to deal with those times when production cannot keep up with demand due to production system variability, we have on average one idle resource that we are paying for. This is not lean.

Another possible approach for dealing with times when production cannot keep up with demand due to variability is to keep capacity equal to what is necessary to meet the long-run average demand (four), and then utilized them at 100%. The result is that during those times when demand is lower than capacity due to some combination of product demand being lower than average, product work content being lower than average, process performance beings better than average, and resource availability being higher than average, the production system produces extra products that then must be kept in inventory to be sold during the times when production capacity is less than demand. This, however, results in inventory-related costs and is also not lean.

Alternatively, one could attempt to adjust resource capacity through the use of overtime, hiring and firing, and subcontracting to exactly counteract the system's variability and thus exactly meet demand without any build-up of inventory. But this approach will result in costs associated with more rigorous forecasting, more detailed production planning and scheduling, and greatly increased production resource management. Also, there are costs associated directly with overtime, hiring and firing, and subcontracting. So although this approach is lean, with no excess capacity or inventory, it does not come for free.

This example is intended to help demonstrate that a fundamental prerequisite to successful lean production is the minimization of variability in the enterprise. This includes demand variability, product and intermediate product work content variability, process performance variability, and variability in resource availability. As' variability is minimized, production process capacities can be balanced, excess capacity can be minimized, and inventory buffers can be dramatically reduced, creating a truly lean manufacturing enterprise.

Substantial problems occur if one attempts to continually reduce inventory and excess capacity in a production system that has any significant variability. If this is done, work disruption will increase and starved resources will become prevalent, resulting in greatly decreased resource utilization and throughput. This is why it is necessary to allow inventory to vary, and/or to allow for some excess and varying capacity within production environments with inherent variability of one kind or another-to absorb the system's variability so as to maintain production output, and minimize disruption and overall production cost. Such intentional use of inventory and excess and varying capacity is fundamentally not lean.

A shipyard can and should do everything possible to improve process performance and minimize variability within the enterprise. Standard materials, components, and modules should be used whenever possible (34,35). Where standards are not possible, group technology should be implemented to the greatest extent possible. Then block boundaries should be defined such that different blocks of each type have a similar amount of assembly work content. Subassembly and fabrication work packages for particular work centers should be defined to include similar amounts of work. Sequencing and scheduling can be improved to minimize resource-specific demand variability. **In** addition, other world-class-manufacturing practices identified earlier can be employed to improve and minimize the variability of process performance.

Bur even after doing all of these things, intermediate product attribute variability within a typical shipyard is still going to be significantly greater than that within the majority of other industries. **In** addition, demand variability can be substantial for a typical shipyard, particularly at the individual work center and resource level. For these reasons, the fact is that there is substantial inherent variability within the typical shipbuilding enterprise. This inherent variability will fundamentally limit the degree to which the t~pical shipyard will be able to minimize excess capacity and/or inventory while cost effectively maintaining output.

So the relevant question for a typical shipyard is not, how do we become lean, but, in what way, and how much, should we vary capacity and inventory through time to meet demand at a minimum overall cost?

First of all, discrete events simulation tools can be utilized in the initial design of facilities to define inventory buffer sizes and the capacity of specific resources so as to minimize overall disruption and production costs for the anticipated mix of products and intermediate products. There are numerous commercially available simulation tools that can be used for this purpose, including GPSS, Arena, ProModel, Quest, and Simple++.

For an operational facility, Aggregate Production Planning (APP) can be used to help derive an optimum inventory and capacity strategy as part of the medium-range planning process. APP uses linear programming methods to solve for the least cost periodic combination of internal resources, overtime, subcontracting, and inventory levels to meet anticipated periodic and overall demand through the medium-range-planning time horizon. This type of optimization can be done using a spreadsheet and its solver, or specialized mathematical modeling and optimization software. The APP process has been used for many years by many industries, and the methodology is covered in most basic operations management textbooks. Narasimhan et al (36) and Chase et al (37) each do a good job of introducing the subject.

Full-scale APPs can incorporate multiple trades and trade classifications with associated varying costs and productivity levels, any type of production resource or subcontractor, overtime, different types of inventory with different associated holding costs, and purchasing discount mechanisms to shift demand between periods, and other factors, as well.

Following is a simple APP example that includes a single trade and a single subcontractor with identical capabilities. The objective is to derive the lowest-cost aggregate production plan or strategy for producing the required quarterly output of this trade by cost-effectively utilizing and changing in-house employment, subcontracting, and inventory levels throughout this time period. This example is done using Excel and its add-in solver.

In this example, demand, inventory, and output are all represented in labor-hour content. Required demand for this particular trade over the next eight quarter is estimated as follows:

Quarter 1	236 000 labor hours
Quarter 2	247000 labor hours
Quarter 3'	252 000 labor hours
Quarter 4	259 000 labor hours
Quarter 5	250 000 labor hours
Quarter 6	243 000 labor hours
Quarter 7	252 000 labor hours
Quarter 8	259 000 labor hours

Initial resource levels are 490 in-house employees and zero subcontract workers. Salaries and subcontracting costs are calculated for each quarter based on each quarter's employment and subcontracting levels, respectively. The example assumes 480 labor hours per worker per quarter. Hiring and firing costs for each quarter appear if there is any difference in employment levels from the previous quarter. Inventory costs per quarter are calculated based on the average inventory for that quarter, which, in turn, is calculated as the average of the current and the previous quarters' end-of-quarter inventories. End-of-quarter inventory is determined by subtracting the current quarter's required demand from the available output. Available output that can be used to meet demand each quarter is the sum of labor hours used in that quarter (in-house plus subcontracting) and the previous quarter's end-of-quarter inventory.

Totals costs through the eight quarters are calculated for salaries, subcontracting, hiring and firing, and inventory, and then these are totaled to determine overall plan/strategy cost. The solver is set to minimizing this overall plan/strategy cost. Each quarter's available output must be greater than or equal to its associated demand. Additional constraints entered into the solver are that internal labor, subcontract labor, and inventory levels must each be greater than or equal to zero for each quarter (cannot have negative employees, subcontractors, or inventory).

In the initial scenario, labor cost per in-house employee per quarter is $20000. Hiring cost is $27 500 and firing cost is $12 000. Cost per subcontracted laborer per quarter is $24000. Initial inventory is 15000 labor hours or about four days work for the current workforce. Inventory-related cost is $1 per labor hour of inventory per quarter. The results, Figure 25.27, show that given this particular scenario the least-cost plan/strategy is to immediately hire 25 employees, then use the resulting periodic excess in-house capacity together with minimal subcontracting to produce inventory as necessary to absorb the variability in demand. In fact, substantial additional inventory is built initially, and then it is worked off and then increases again through time.

One lean approach to meeting demand would be to work off the initial inventory as quickly as possible, maintain constant in-house labor, and then vary subcontracting as necessary to exactly meet demand. However, this approach would be about $9000 more costly than the non-lean solution derived for this scenario. Another lean approach would be to work off the initial inventory as quickly as possible and then vary in-house labor as necessary to exactly meet demand without the use of subcontracting. However, this approach would be $1.8 million more costly than the solution derived for this scenario.

Another shipyard might have different constraints. For example, assume another yard has higher inventory-related costs because of the scarcity and higher cost of space and a higher cost of capital-say $2.50 per labor hour of inventory per quarter. All other costs are the same as those in the previous scenario. The resulting least-cost plan/strategy, Figure 25.28, is very different from that ofthe first scenario, and is, in fact, one of the lean solutions identified above. In-house employment is kept constant. Inventory is reduced very quickly and kept out of the system because of its high cost. And varying subcontracting is used to absorb all system variability. The alternative lean approach, varying in-house labor as necessary and using no subcontracting, would be $1.8 million more costly. This is because the cost of hiring and firing in-house employees as necessary over time would be substantially greater that the premium being paid for the required subcontracted workers.

If hiring and firing costs were lower, however, this strategy might change. Say a third yard has the same high inventory cost but substantially lower hiring and firing costs, say $9000 and $0, respectively, due to the higher availability of skilled labor and no union. The resulting least-cost plan/strategy, Figure 25.29, initially and quickly reduces inventory levels, but then variability is absorbed through in-house hiring and firing, together with some later inventory. In this case, the lean solution of eliminating initial inventory and varying subcontracting to exactly meet demand

Quarter	Req'd Demand (LH)	Internal Labor	Salaries	Hiring/Firing Cost	Subcontract Labor	Subcontract Cost	Used LH	Ending Inventory (LH)	Inventory Cost	Available Output (LH)
NOW		490			0			15,000		
1	**236,000**	515.0	$ 10,300,862	$ 688,685	0.0	$ -	247,221	26,221	$ 20,610	**262,221**
2	**247,000**	515.0	$ 10,300,874	$ 16	0.9	$ 22,201	247,665	26,886	$ 26,553	**273,886**
3	**252,000**	515.0	$ 10,300,897	$ 32	1.2	$ 28,778	247,797	22,683	$ 24,784	**274,683**
4	**259,000**	515.0	$ 10,300,910	$ 18	0.0	$ -	247,222	10,905	$ 16,794	**269,905**
5	**250,000**	515.0	$ 10,300,911	$ 3	1.8	$ 42,413	248,070	8,975	$ 9,940	**258,975**
6	**243,000**	515.0	$ 10,300,912	$ 0	2.0	$ 49,173	248,205	14,180	$ 11,577	**257,180**
7	**252,000**	515.0	$ 10,300,915	$ 5	2.3	$ 56,025	248,342	10,523	$ 12,351	**262,523**
8	**259,000**	515.0	$ 10,300,915	$ 0	2.6	$ 62,775	248,477	0	$ 5,261	**259,000**
TOTALS			**$ 82,407,195**	**$ 688,759**		**$ 261,366**			**$ 127,871**	

Labor Hours/employee or subcontracted laborer/quarter	480
Labor Cost/in-house employee/quarter	$ 20,000
Hiring Cost	$ 27,500
Firing Cost	$ 12,000
Cost/subcontracted laborer/quarter	$ 24,000
Inventory Cost/labor hour of inventory/quarter	$ 1.00

TOTAL COST: $83,485,191

Figure 25.27 Example Aggregate Production Planning Scenario 1 Results would be $457 000 more costly than the derived non-lean solution. And the lean solution of eliminating initial inventory and varying in-house labor to exactly meet demand would be $358 000 more costly than the derived non-lean solution.

These examples demonstrate, and, in fact, real-world experience confirms, that different situations call for different strategies for the use of capacity, capacity variation, and inventory. Scenarios one and three above show that given particular constraints, excess capacity and inventory can be beneficial. The second scenario resulted in a lean enterprise with no excess capacity or inventory. But this solution was derived from the objective consideration and economic analysis of relevant constraints, not from some philosophical desire to become lean. It is also important to remember that relevant constraints can change through time, so a shipyard's strategy for the use of capacity and inventory should be reevaluated as constraints change.

25.4 SUMMARY

The primary product characteristics that drive the shipbuilding process are demand and demand variability, size and complexity, mobility, material, variety and variability. The appropriate shipbuilding process will depend on the combination of product attributes present.

For very unique and low-volume complex marine products, a construction approach is most appropriate. The construction approach has a low level of capital intensity

Quarter	Req'd Demand (LH)	Internal Labor	Salaries	Hiring/Firing Cost	Subcontract Labor	Subcontract Cost	Used LH	Ending Inventory (LH)	Inventory Cost	Available Output (LH)
NOW		490			0			15,000		
1	**236,000**	490.0	$ 9,800,000	$ -	0.0	$ -	235,200	14,200	$ 36,500	**250,200**
2	**247,000**	490.0	$ 9,800,000	$ -	0.0	$ -	235,200	2,400	$ 20,750	**249,400**
3	**252,000**	490.0	$ 9,800,000	$ -	30.0	$ 720,000	249,600	0	$ 3,000	**252,000**
4	**259,000**	490.0	$ 9,800,000	$ -	49.6	$ 1,190,000	259,000	0	$ -	**259,000**
5	**250,000**	490.0	$ 9,800,000	$ -	30.8	$ 740,000	250,000	0	$ -	**250,000**
6	**243,000**	490.0	$ 9,800,000	$ -	16.3	$ 390,000	243,000	0	$ -	**243,000**
7	**252,000**	490.0	$ 9,800,000	$ -	35.0	$ 840,000	252,000	0	$ -	**252,000**
8	**259,000**	490.0	$ 9,800,000	$ -	49.6	$ 1,190,000	259,000	0	$ -	**259,000**
TOTALS			**$ 78,400,000**	**$ -**		**$ 5,070,000**			**$ 60,250**	

Labor Hours/employee or subcontracted laborer/quarter	480
Labor Cost/in-house employee/quarter	$ 20,000
Hiring Cost	$ 27,500
Firing Cost	$ 12,000
Cost/subcontracted laborer/quarter	$ 24,000
Inventory Cost/labor hour of inventory/quarter	$ 2.50

TOTAL COST: $83,530,250

Figure 25.28 Example Aggregate Production Planning Scenario 2 Results

Quarter	Req'd Demand (LH)	Internal Labor	Salaries	Hiring/Firing Cost	Subcontract Labor	Subcontract Cost	Used LH	Ending Inventory (LH)	Inventory Cost	Available Output (LH)
NOW		490			0			15,000		
1	**236,000**	490.1	$ 9,801,800	$ 810	0.0	$ -	235,243	14,243	$ 36,554	**250,243**
2	**247,000**	510.0	$ 10,199,808	$ 179,104	0.0	$ -	244,795	12,039	$ 32,852	**259,039**
3	**252,000**	516.5	$ 10,330,444	$ 58,786	0.0	$ -	247,931	7,969	$ 25,010	**259,969**
4	**259,000**	523.0	$ 10,459,615	$ 58,127	0.0	$ -	251,031	0	$ 9,962	**259,000**
5	**250,000**	523.1	$ 10,461,315	$ 765	0.0	$ 1,129	251,094	1,094	$ 1,368	**251,094**
6	**243,000**	522.8	$ 10,456,401	$ -	0.1	$ 1,353	250,981	9,075	$ 12,711	**252,075**
7	**252,000**	522.8	$ 10,455,618	$ -	0.1	$ 1,576	250,966	8,041	$ 21,395	**260,041**
8	**259,000**	522.8	$ 10,455,118	$ -	0.1	$ 1,800	250,959	0	$ 10,051	**259,000**
TOTALS			**$ 82,620,119**	**$ 297,592**		**$ 5,857**			**$ 149,903**	

Labor Hours/employee or subcontracted laborer/quarter	480
Labor Cost/in-house employee/quarter	$ 20,000
Hiring Cost	$ 9,000
Firing Cost	$ -
Cost/subcontracted laborer/quarter	$ 24,000
Inventory Cost/labor hour of inventory/quarter	$ 2.50

TOTAL COST: $83,073,471

Figure 25.29 Example Aggregate Production Planning Scenario 3 Results because product and intermediate product volume by type is not sufficient to justify large expenditures on specialized production equipment and facilities. This necessarily limits the amount of subassembly and modularization possible and results in much *stick-building* and outfitting on and within the final structure, similar to commercial building and factory construction. Labor productivity is also similar to that of the commercial building and factory construction industry.

For standard ships built in high volume, a tightly integrated manufacturing approach is most appropriate. Such a production system has many levels of subassembly and utilizes a great deal of structural and outfitting modularization. This production approach is similar to that used for commercial aircraft manufacturing. Because of the high degree of product and intermediate product standardization and the high production volume, significant investment in specialized production facilities and equipment can be justified. Labor productivity on average is about 2.5 times that of the marine product construction approach. Shipyards that build standard ships in high volume make up only a very small portion ofthe shipbuilding industry because the market for standard ships is quite small.

The vast majority of shipyards build multiple ships simultaneously with some variety in ship type and some variability between ships of the same type. These shipyards utilize a GT-based approach to production in order to exploit to the greatest extent possible the similarities between non-identical products and intermediate products. The GT-based ship production system is similar to the system used for standard ships, with virtually identical material and work flow, and degree of subassembly and modularization. However, the GT-based shipbuilding system is somewhat less tightly integrated with additional excess capacity and inventory buffers to absorb the inherently greater degre~ of demand and work content variability in the system. A GT-based shipbuilding system will also employ somewhat less automation than a shipyard building standard ships because of the need for greater flexibility. Labor productivity in a GT-based ship production system is 1.5 to 2 times higher than that of the marine product construction approach.

Most world-class manufacturing principles apply to shipbuilding just as well as they apply to any other industry. However, the fundamental lean objectives of simultaneously minimizing inventories and excess capacity apply only to a limited degree to the vast majority of shipbuilding enterprises because of the inherent variability that is common to their production systems. In these situations, aggregate production planning techniques should be utilized to determine optimal levels and types of capacity and inventory to minimize overall production cost. There is much greater opportunity to obtain lean objectives in the few shipyards that produce standard products.

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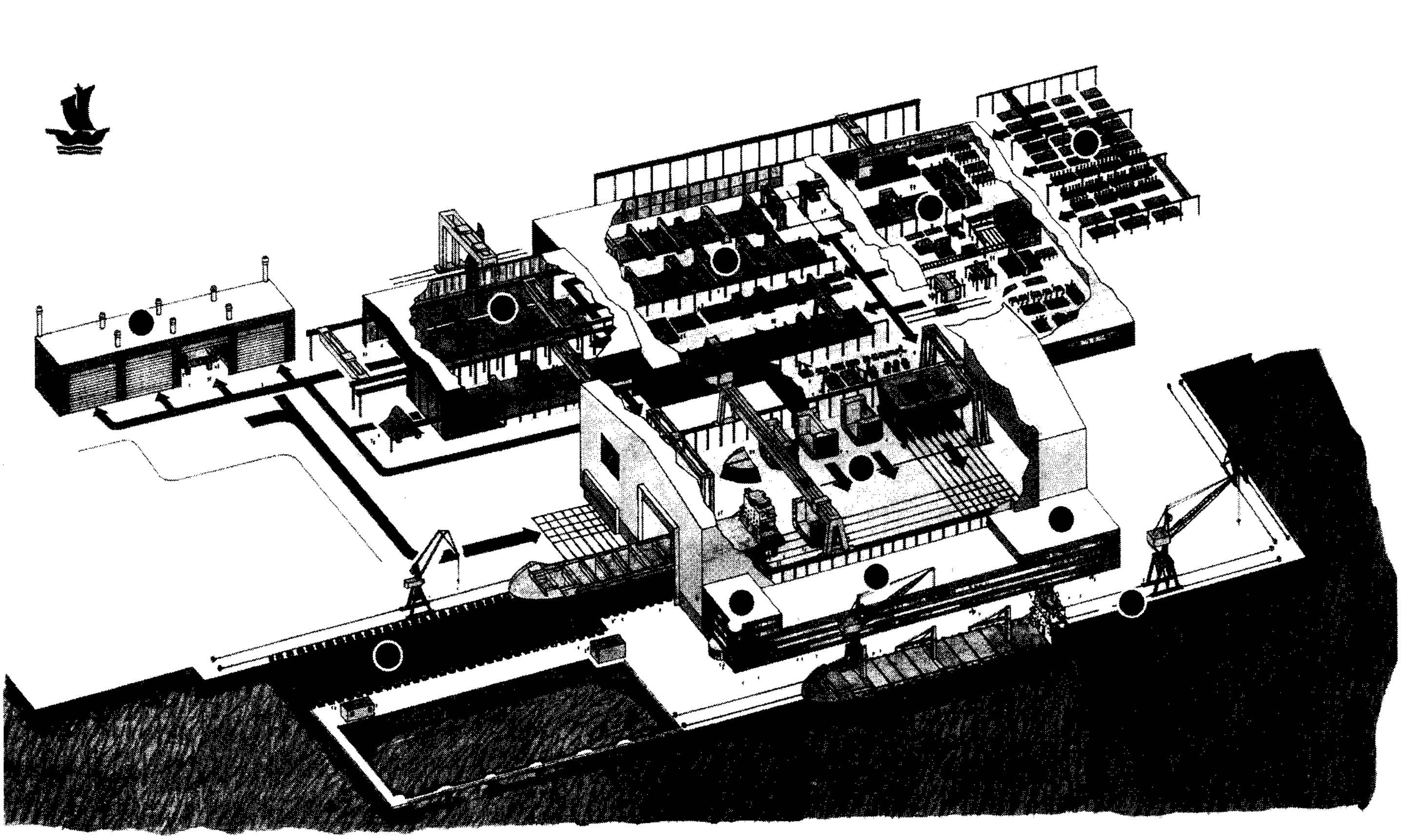

Chapter 26

Shipyard Layout and Equipment

Thomas Lamb

26.1 INTRODUCTION

It is obvious that the ship designer should know and appreciate the capabilities and constraints of a shipyard in order to ensure that the best design is prepared for that shipyard. It is wrong to assume that the same design can be built with the same productivity, in a number of different shipyards, unless the shipyard facilities and building practices are identical.

It is, therefore, necessary for ship designers to have an appreciation of shipbuilding facilities and the equipment utilized by them. There is a wide range of shipyard layouts and they can influence the design and the efficiency with which it is built.

The shipbuilding practices also vary, but there is a basic process used by all of them, but to varying degrees, ~ich is discussed in Chapter 25. Like wise there is equipment that will be found in most shipyards, but again its use can vary.

The purpose of this chapter is to describe some of them so that the reader can identify and better appreciate the impact of the shipyard layout and equipment of their shipyard on their designs.

Additional information on shipyard layout can be found in Ship Production (1) also published by SNAME.

26.2 BRIEF HISTORY

Shipbuilding practices and the layout of the shipyards have developed over a long period of time as both the ships being built and the production technology have changed. The shipyard layouts also had to suit the natural environments in which they were placed.

Most shipyards are located on riverbanks or the shores of bays, protected from the open sea. The method of moving the ship from land to the water depended on tide and shipyard configuration.

Drydocks (Graving Docks) were used for building ships as early as the 16th century in Venice and for the building of the Royal Navy's large *ships of the line* in the 18th century. Side launching of ships (Figure 26.1) goes back to antiquity with two famous side launched ships being Cleopatra's Barge and Brunell's *Great Eastern.* Nearer home, most of the Gulf Coast and Great Lakes shipyards use the side launch method.

Many of the Great Lakes large bulk carriers were side launched, though in the last 20 years they have almost all been built in a drydock.

End launching (Figure 26.2) is equally old and until the modem development of drydocks for shipbuilding, which started in the 1960s, was the most common methods used by the world's shipbuilders. Launching by floating dock and ship elevators is a relatively recent (since 1960s) development.

The natural land topography found along riverbanks influenced the shipyard layout. Figure 26.3 shows the basic layouts based on shape and material flow within the shipyard. Some shipyards were developed where there was restricted water frontage but lots of depth, such as shown in Figure 26.3a. This naturally led to a straight-line flow of materials, thus this layout is called *deep, narrow* or *straight-line flow* type.

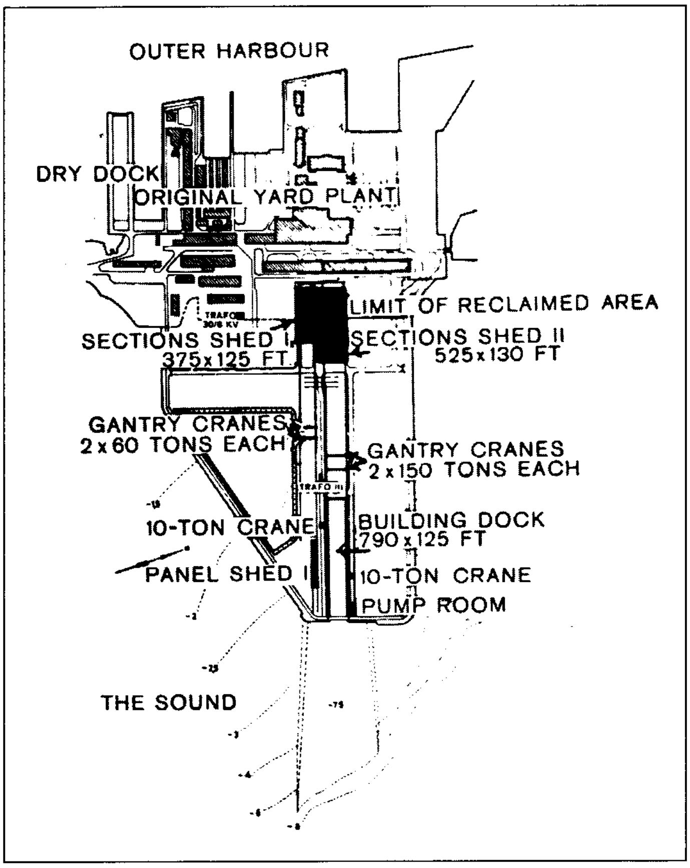

Figure 26.5 B&W Shipyard, Copenhagen, Denmark

Figure 26.6 Arendal Shipyard, Sweden

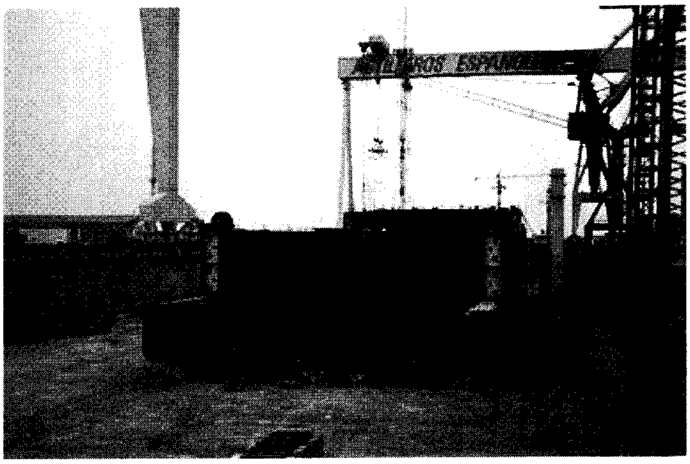

Figure 26.7 A Building Dock

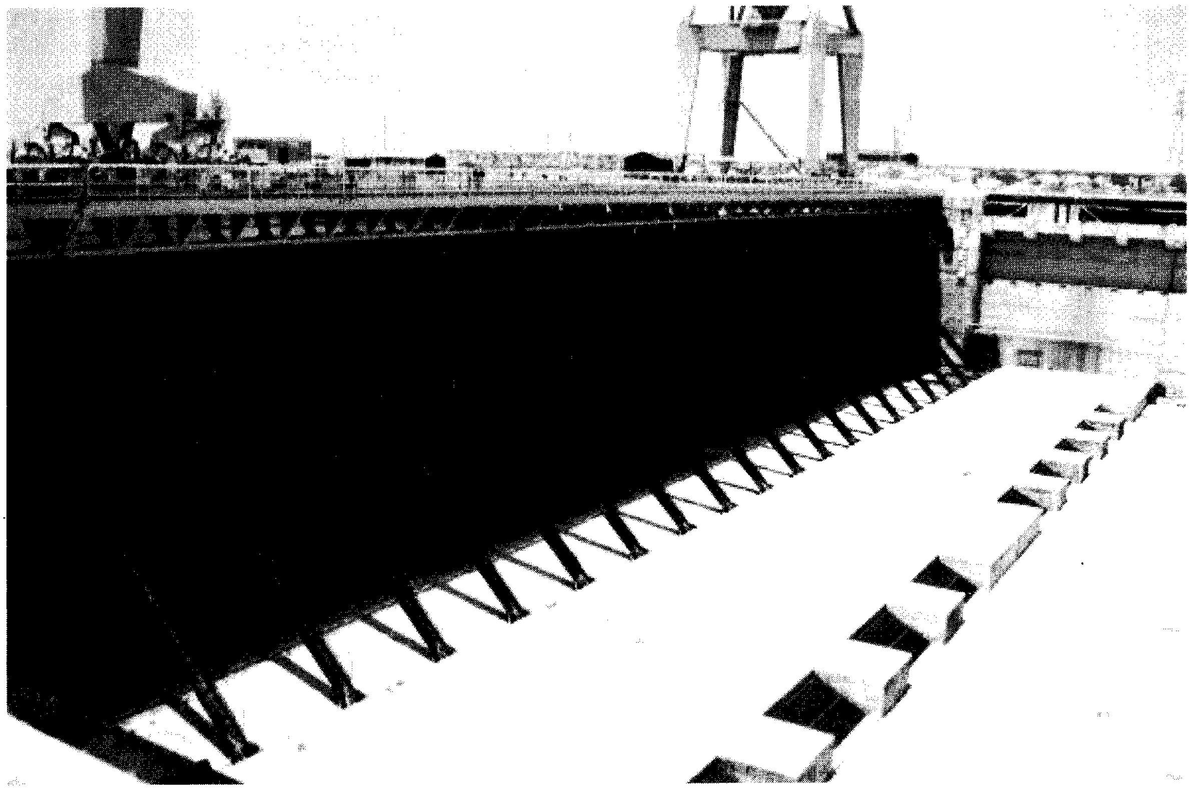

Figure 26.8 Movable Dock Gate

their ships on inclined building berths (Figures 26.9) and traditionally end launch them as shown in Figure 26.2. The B&W shipyard used part of its existing shipyard for the steel preparation and fabrication and was not a *true* straight-line flow. However the Arendal shipyard was designed from the start as a continuous straight-line flow layout, as shown in Figure 26.10. It also utilized the *ship extrusion* approach. It is sad to say that both shipyards are closed.

Most other shipyards are variations of this type trying to seek a happy medium of shape to suit their location. Many Japanese shipyards are almost square as shown in Figures 26.11 and 26.12. **In** addition the Japanese shipyard layout is either a *T* or a *U* layout (Figure 26.13).

Ingalls's shipyard in Pascagoula is also square in shape as shown in Figure 26.14, but uses a floating dock for launching whereas most of the other examples used graving docks. It is unique in its shipbuilding approach having process lines for the different portions of a ship, as shown in Figure 26.15, where the flow of the ship portions can be clearly seen as they move from right to left.

In the mid-1970s the original *ship factory* was developed by Appledore in Devon, England and was later used to modernize two other larger shipyards in the same shipbuilding family in Sunderland, in the North East of England (3). The layout of the ship factories is shown in Figures 26.16 and 26.17.

The compactness as well as the covered building dock were hallmarks of this type.

While Korea has continued to build new shipyards as well as expand the facilities of existing shipyards, the only other new shipyards are being built in China. Germany has completely renovated some of the existing East German shipyards (Figure 26.17 and 18) while many West German shipyards have closed down.

All existing shipyards have undertaken significant reorganization in order to stay in the highly competitive international shipbuilding market, which is driven by low prices due to over capacity. That is, there are too many shipbuilders chasing too few ship orders.

Other non-equipment improvements that parallel the equipment improvements are weld through primer, immediate repair of process damaged primer by process worker and elimination of need to re-blast block before final block painting.

The new and remodeled shipyards concentrate on in-

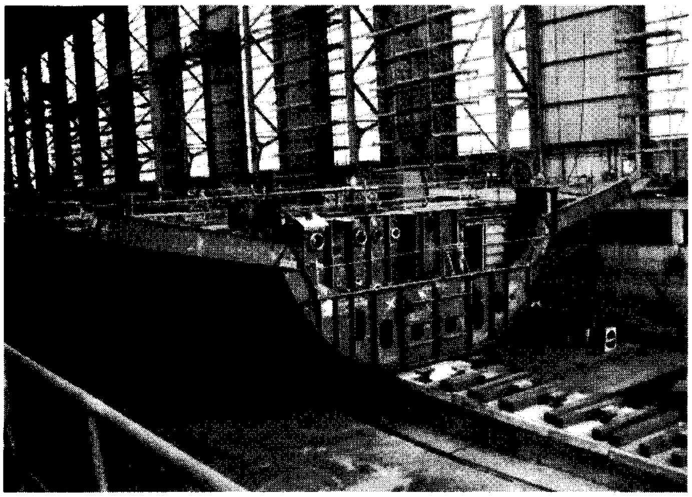

Figure 26.9 An Inclined Building Berth

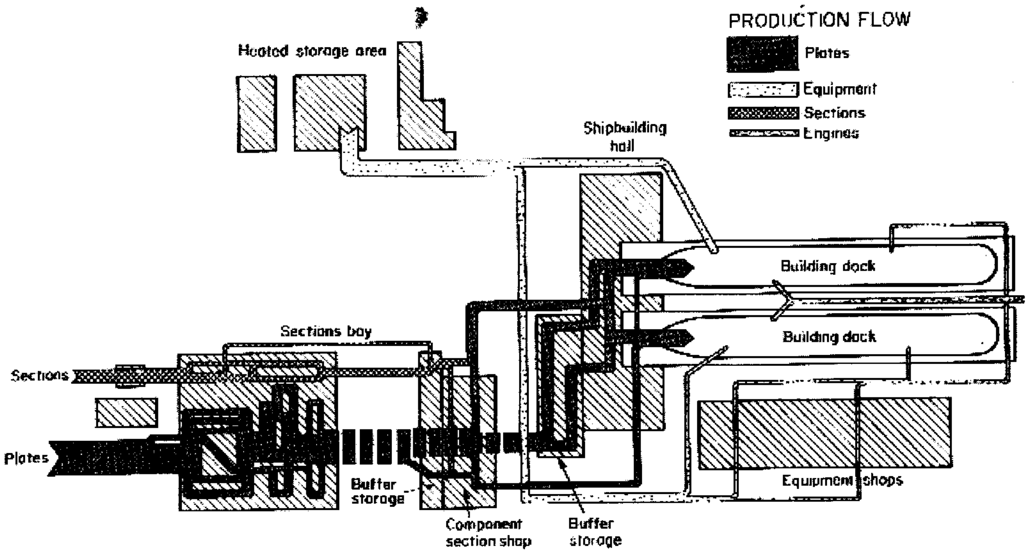

Figure 26.10 Arendal Straight-line Production Flow

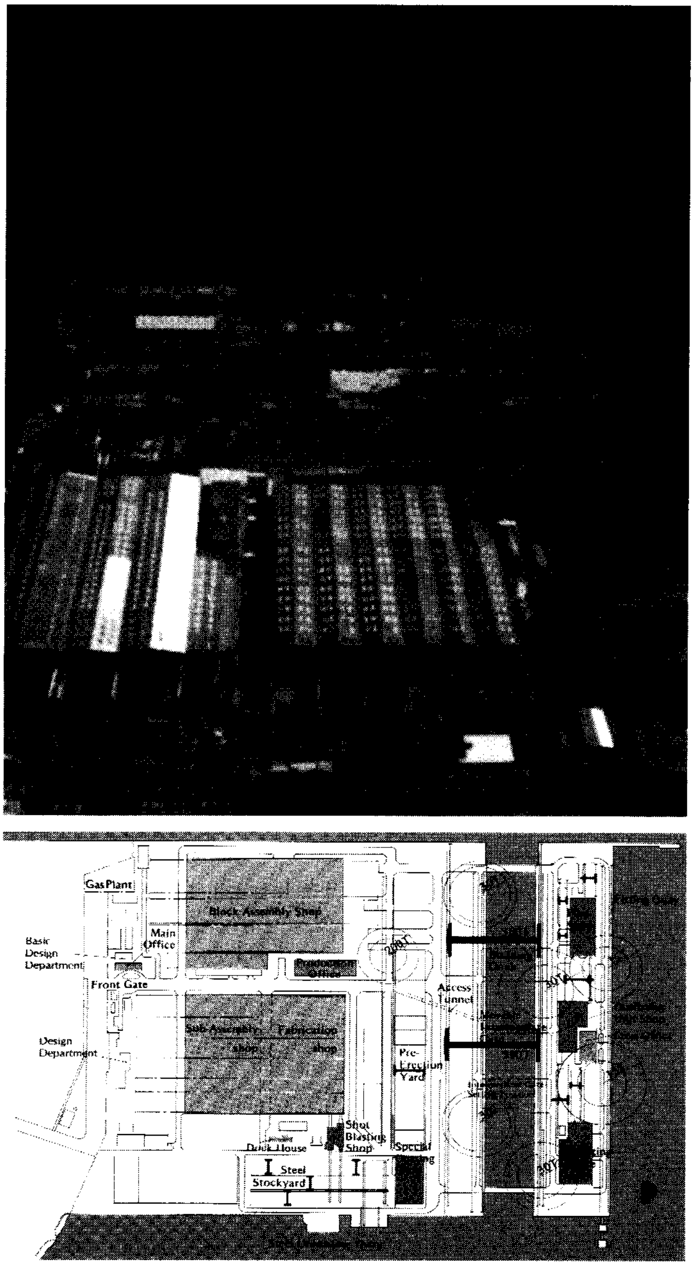

Figure 26.11 Square-shaped Japanese Shipyard with *T* Layout (Oppama)

Figure 26.12 Almost Square-shaped Japanese Shipyard again with *T* Layout (Mitsubishi)

stalling new equipment that helps them improve in four areas of shipbuilding, namely,

1. structural fabrication and assembly (steel shops),
2. pipe fabrication (pipe shop),
3. advanced outfitting (package unit shop), and
4. building berth.

The improvements in steel shops include:

- laser cutting and marking
- both wet and dry plasma cutting and marking of plate parts,
- automatic cartridge stowage systems for structural profiles,
- robot profile line,
- one sided welding,
- laser welding,
- panel cutting (perimeter) and marking,

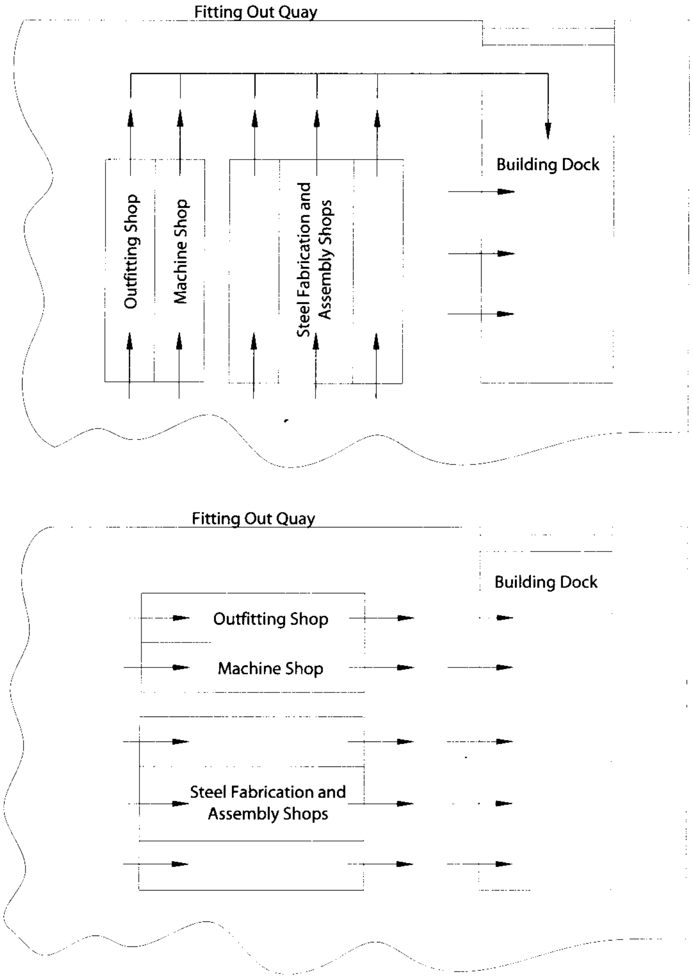

Figure 26.13 T and U Flow Shipyard Layouts

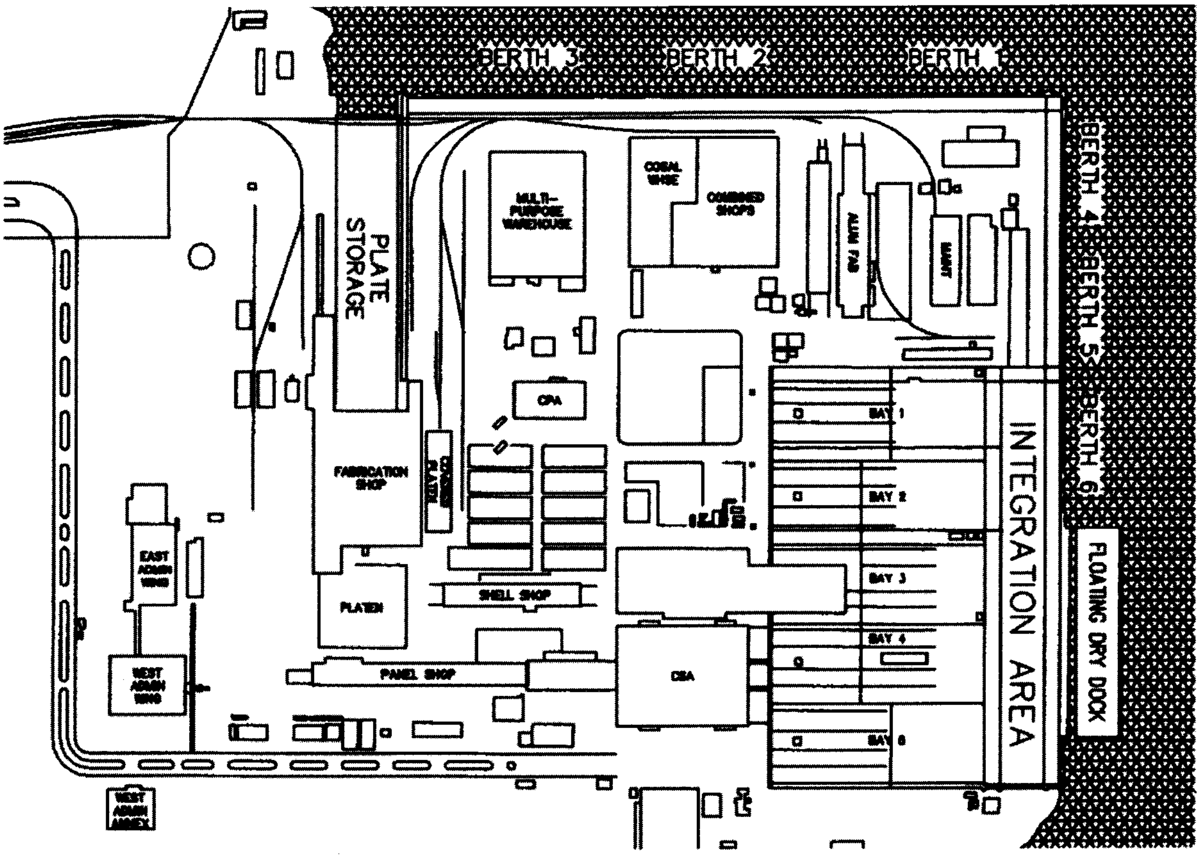

Figure 26.14 Northrop Grumman Shipbuilding Systems (Ingalls) Shipyard (Pascagoula)

Figure 26.15 Northrop Grumman Shipbuilding Systems (Ingalls) Shipbuilding Ship Construction Flow

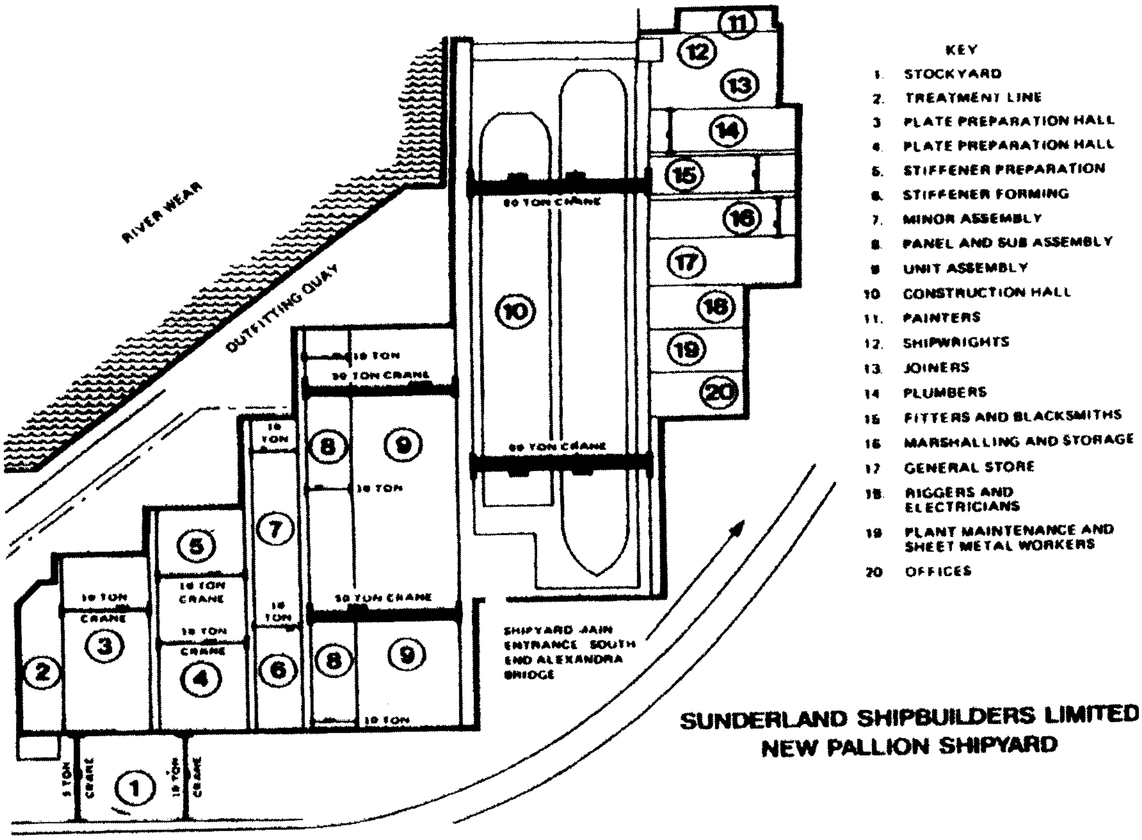

Figure 26.16 Layout of the Pallion Ship Factory

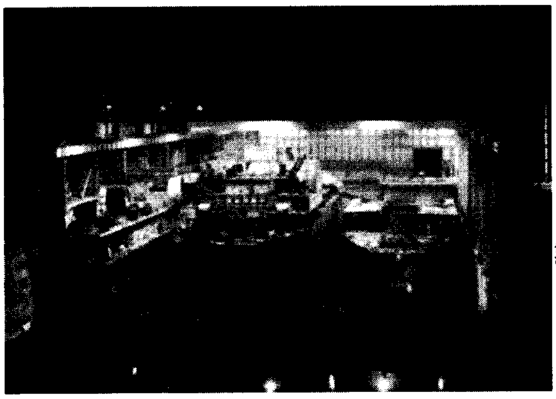

Figure 26.17 The *Second* Ship Factory (Austin & Pickersgill Pallion Shipyard)

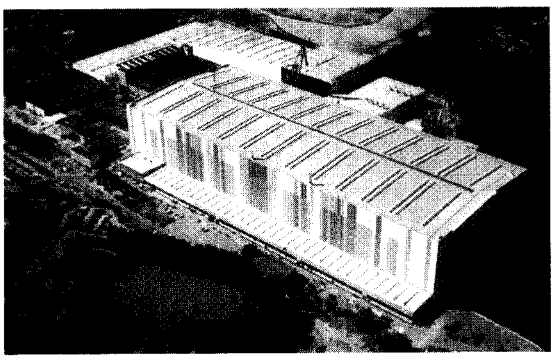

Figure 26.18 MTW *Compact* Shipyard in Wismar, Germany

- large and small panel lines with robot stiffener welding, robot welding for web frames,
- pin jigs on movable platform to provide limited panel line flow to curved block construction, and
- grand block construction.

The enclosing of t~e building berth, slipway or dock, as shown in Figures 26.9, 26.18 and 26.19, is the most recent trend, mostly in countries affected by significant bad weather, such as Northern Europe.

Figures 26.20 and 26.21 show typical current steel shop layout and processing lines.

There has been a general trend to move as much work as possible into the steel shops and minimizing time on the building berth. This requires larger covered areas for structural and advanced outfitting work. Another trend in European shipyards is the compact shipyard where all the shops are connected together with minimum buffer space as shown in Figure 26.22, which is the remodeled MTW shipyard in Wismar, Germany.

In some ways this is similar to the Ship Factory concept developed by Appledore (Figure 26.16), and even the steel shop arrangement at Odense Steel Shipyard shown in Figure 26.23, even though, in this case, the building dock is not adjacent to the shops.

Recent new Korean shipyards still follow the expansive

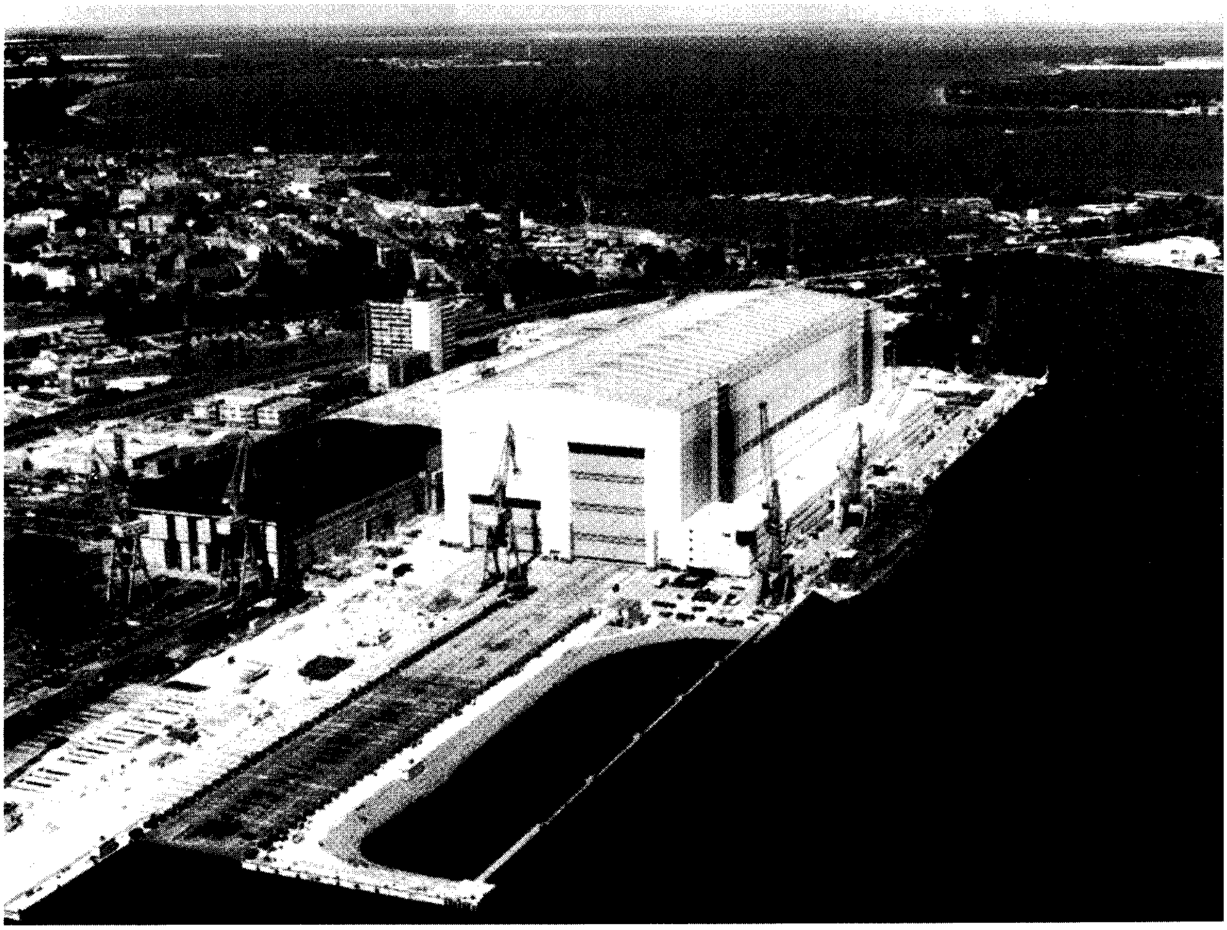

Figure 26.19 A. P. Moller Volkswerft Stralsund Shipyard, Germany

layout where there are great spaces between the fabrication shop, the assembly shop, the paint halls, and the building berth as shown in Figure 26.24, which is the Sambo heavy Industries shipyard. The paint sheds along the upper bound'-ary are far removed from the steel shops and the building berth, requiring extensive travel by transporters.

An older Korean shipyard is Samsung shown in Figure 26.25. Actually it is two shipyards. The original shipyard with two building docks and one repair dock is located at the upper middle of the photograph.

The newer (1997) part can be seen at the lower part of the photograph with only one very large building dock and separate new steel processing facilities.

Recent Japanese shipyard developments are the use of dedicated process lines for double bottom/side blocks and the automatic curved plate shaping machines.

Some shipyard pipe shops are totally automated, although most shipyards seem to keep some manual work, to take care of large, unique or difficult pipe pieces. Robot pipe cutting, flanging, pultrusioning and bending are all required to achieve competitive productivity in moderate to

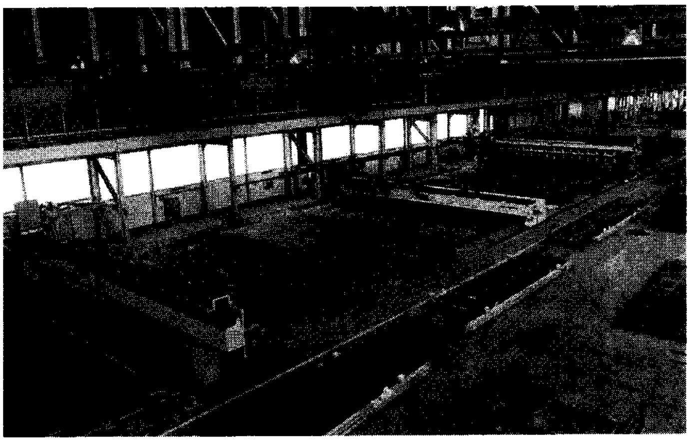

Figure 26.20 Typical Steel Shop (Panel Line)

high volume pipe fabrication. Figure 26.26 is a photograph of a typical pipe shop and Figure 26.27 shows the layout of a shipyard automated pipe shop.

Advanced outfitting (See Chapter 25 - The Shipbuilding Process) is being used by most shipyards although there

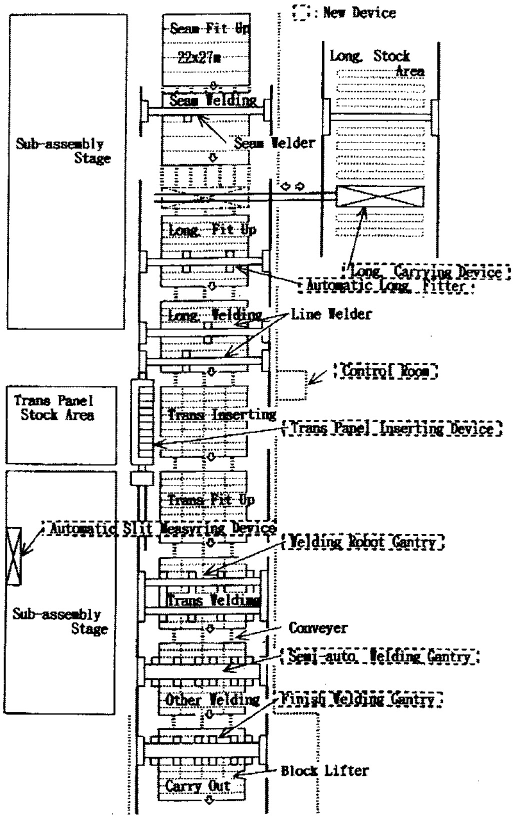

Figure 26.21 Flat Panel Line

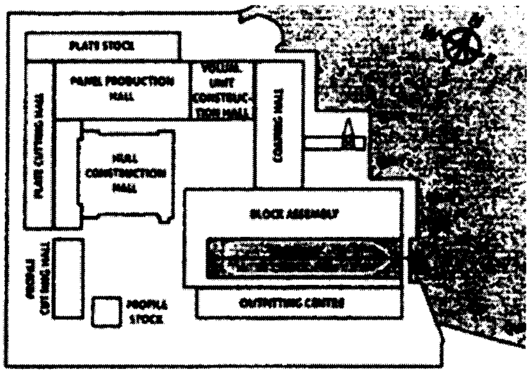

Figure 26.22 MTW *Compact* Shipyard Layout

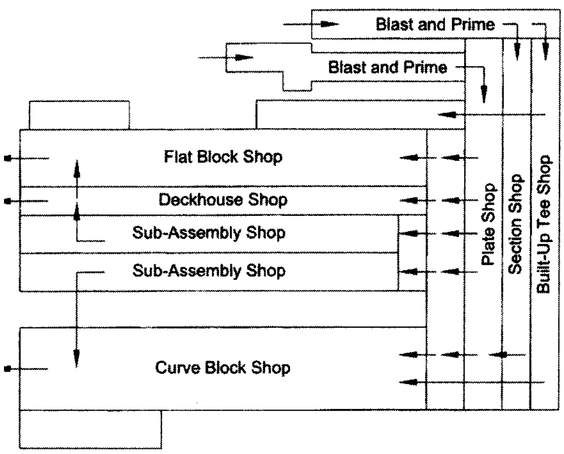

Figure 26.23 Odense Steel Shipyard Steel Shops

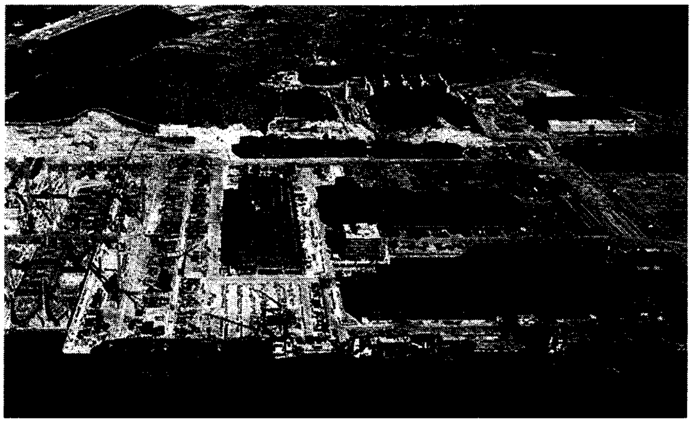

Figure 26.24 Samho Heavy Industries Shipyard in Korea Showing the Large Size and Space between Shops, Paint Halls and Building Dock

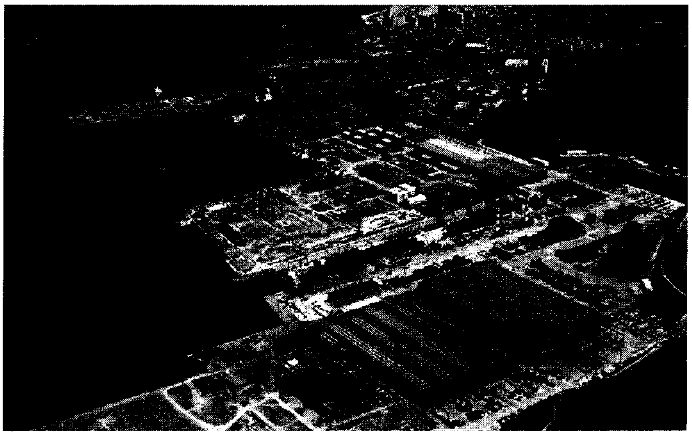

Figure 26.25 Samsung Shipyard, Korea

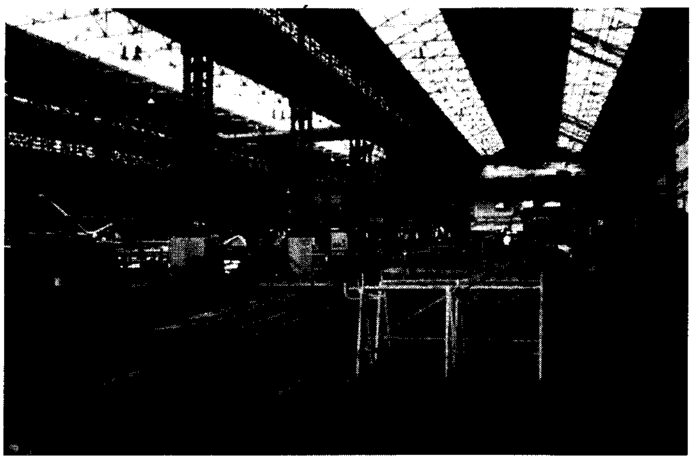

Figure 26.26 Typical Shipyard Pipe Shop

are a few that do not utilize it. Such shipyards usually utilize significant turnkey subcontracting (for all pipe, insulation, electrical, HVAC and coatings). It is easier to manage these sub-cootractors if the ship is completed to a certain stage before the turnkey subcontractor starts his work rather than trying to integrate them with the shipyards workforce and planning to accomplish advanced outfitting.

When advanced outfitting is utilized the trend is for larger and more complete *machinery packaged units,* often many levels high, such as the approach developed by Thyssen (4) Shipyard in Germany and NASSCO in the U.S. (5), such as shown in Figures 26.28 and 26.29, respectively.

There appears to be two trends in block sizes. First, where the building berth is integrated into the main buildings, the approach is to build blocks up to 250 tons.

However. some of the renovated East German compact shipyards have crane capacity to lift up to 800 tonnes inside the building hall. Second, when the building berth is remote from the shops, the approach is to build grand blocks (Figure 26.30) from 700 to 1000 tonnes for crane lift and up to 3000 tonnes when positioned on the building berth by transporters (Figure 26.31) and/or elevators (Figure 26.32). These grand blocks are formed from smaller blocks of up to 200 tonnes.

When the second approach is utilized, it must be decided whether to advance outfit the smaller blocks or wait until the grand block is constructed, the former being preferred.

Finally, most successful shipyards recognize that both steel and ship throughput are important criteria. Although there are many small shipyards that are successful in their product range, to attain the highest productivity, a shipyard requires a minimum throughput of steel, such as 60 000 tonnes and a minimum number of ships per year, such as 4.

The key is that the shipyard facilities must be matched

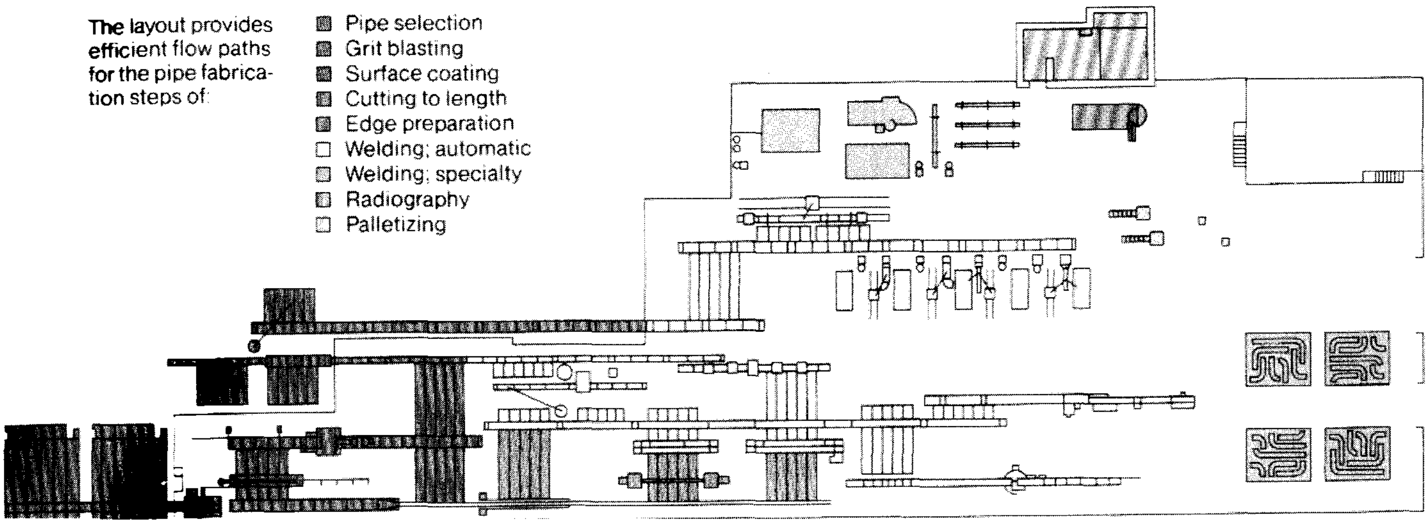

Figure 26.27 Automated Pipe Shop Layout

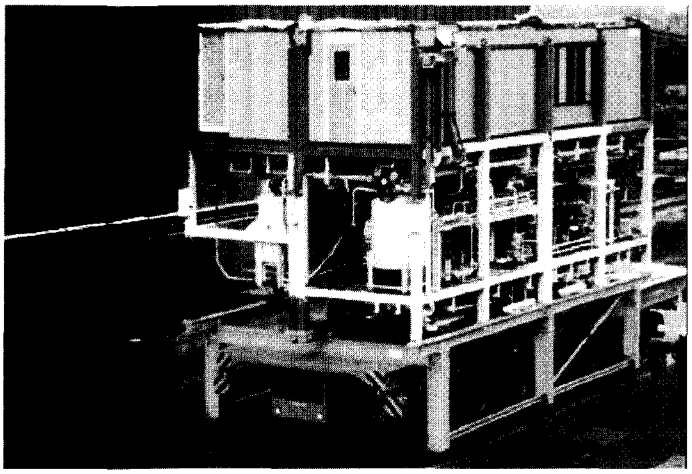

Figure 26.28 Thyssen Machinery Space Unit

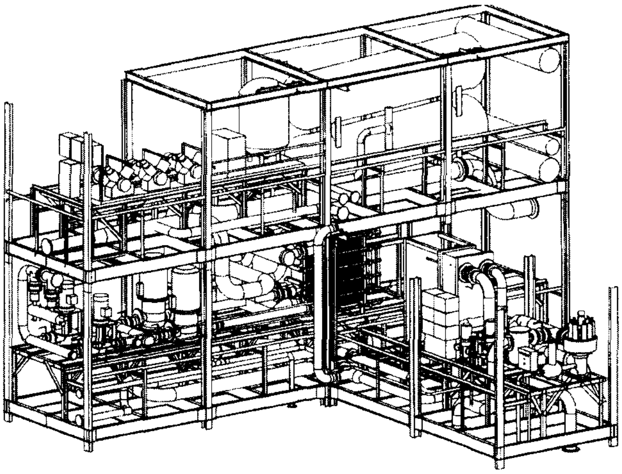

Figure 26.29 NASSCO Machinery Space Unit

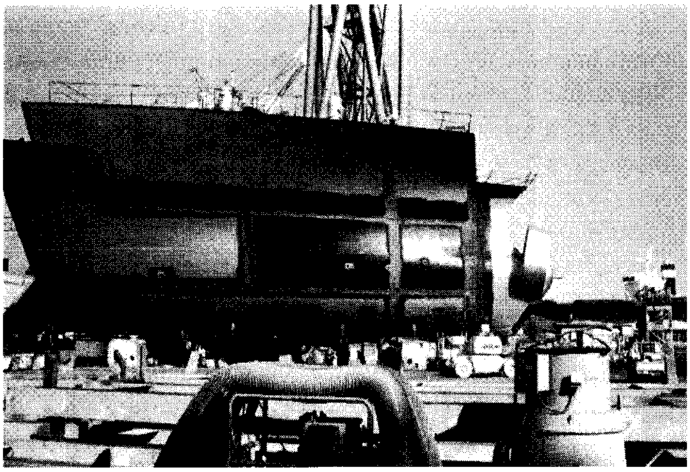

Figure 26.30 Typical Grand Block

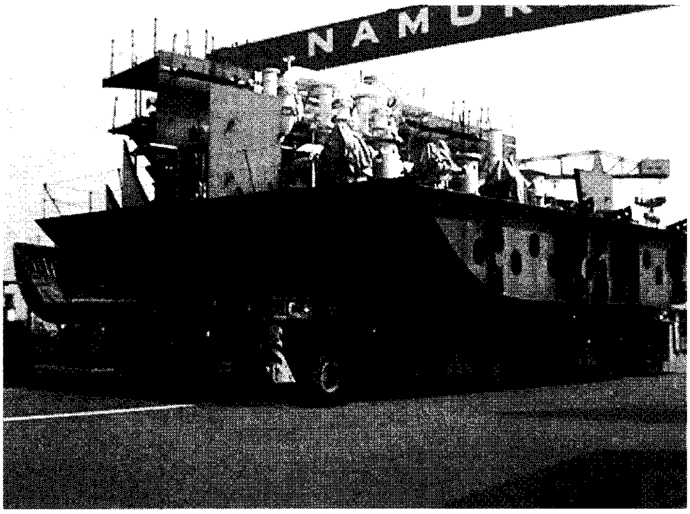

Figure 26.31 Multiwheeled/360° Transporter

Figure 26.32 Building Dock Elevator

with their intended market. Odense Steel Shipyard has 200 000 tonnes of steel throughput and up to 6 ships per year. Hyundai has I 200 000 tonnes and over 60 ships per year.

Interestingly, much of the technology used by modem shipbuilders is not new. It has been around for at least two decades. They have simply kept improving their use of it. The Japanese, in particular, change the basic technology of a process only when they have exhausted its potential benefits arising from relentless analysis of the process. 26.1 lists some recent developments in shipyard facilities and equipment.

Many shipbuilders build small ships (up to 100 m) and all shipyards are not large. While some small shipyards have extensive facilities and equipment (such as the original ship factory, Appledore Shipyard in Devon, England) most are quite simple in layout and equipment. Figure 26.33 shows a typical U.S. small shipyard, where the lack of buildings is noticeable and the ships are side launched.

26.3 SHIPYARD LAYOUT REQUIREMENTS

Shipyard layouts have to suit the natural environments in which they are located. Obviously shipyards should be close to and have deep-water access to the open sea, and land or sea access for delivery of equipment, components and raw material. So most shipyards are located on the banks of rivers or the shores of bays, protected from the open sea.

First, a brief description of a typical modem shipyard, building commercial ships will be used to introduce aspects oflayout and the equipment used. Then details of the equipment will be presented.

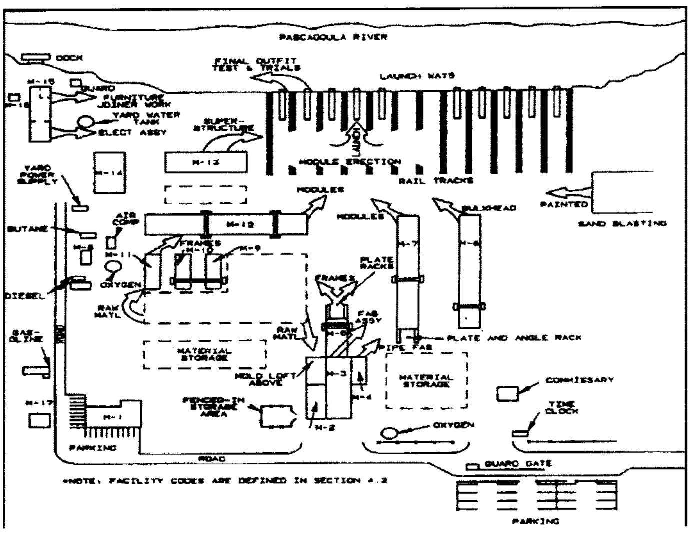

Figure 26.33 Small U.S. Shipyard Layout

The shipyard would be square in shape with deep water on two sides. It would have a *building dock* (a hole in the ground with a gate at one or both ends that would keep the water out when dry and opens to let the ships out when flooded) in which the ship would be assembled.

The chapter frontispiece shows a schematic layout of the *Volksweft Stralsund* shipyard in Germany. It is typical of the *compact* shipyard approach and gives a good visual understanding of the material and product flow.

Steel plate, profiles and pipe would be delivered by ship as would major equipment such as the main engine. The plate would be stored in a *stockyard* (Figure 26.34). The steel profiles and pipe would be stored in *magazines,* which automatically deliver the profiles to the automatic processing machines on demand.

The equipment and processing lines would be located in buildings (Figures 26.35) and within the buildings there would be shops for the processing of steel plate (Figure 26.36) and steel profiles (Figure 26.37), pipe, and outfitting *packaged machinery units.*

Inside these shops would be *overhead cranes* and/or floor mounted *conveyors* to move the parts from one workstation to the next workstation. The *steel processing shops* would consist of three bays or shops. In the first bay, the steel plate would be delivered from the stockyard, to a *blast and prime machine* (Figure 26.38), which would blast, wash, and dry the plate to remove scale and rust and prime coat it to protect the surface during processing.

Note that some shipyards have such a short block build cycle time, from initial blast to completion of blocks including painting, and that the process is completed under cover, so they do not need to prime coat the steel after blasting, as there is no time for the steel to rust.

TABLE 26.1 Recent (Past 10 Years) Shipbuilding Facility and Equipment Development

Dry plasma, laser and water cutting
Plasma marking
Grand block transporters and elevators
Single berth concentration
One-sided welding
Laser welding
Automated pipe shops
Welding robots
Assembly robots
Laser measuring equipment

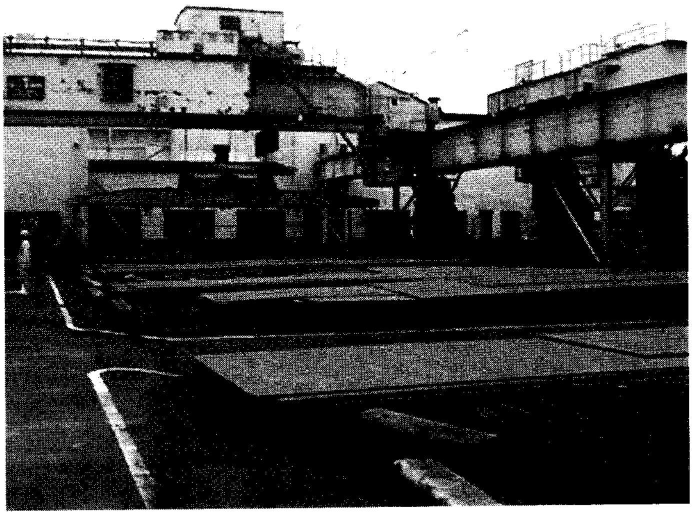

Figure 26.34 Steel Stockyard

Figure 26.35 Typical Shipyard Buildings

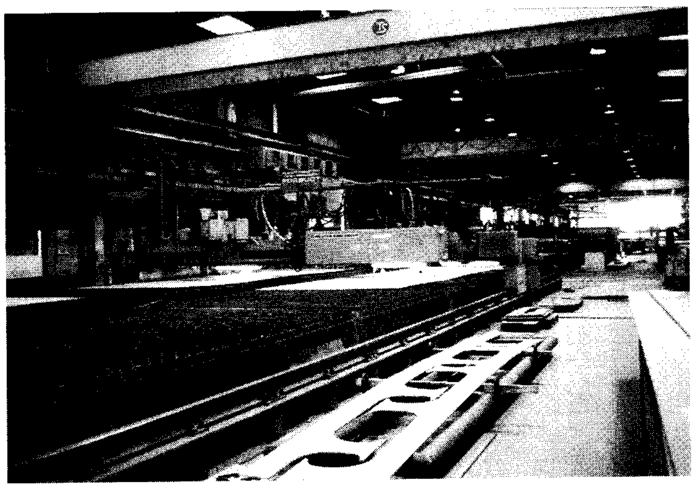

Figure 26.36 Steel Processing Plate Shop

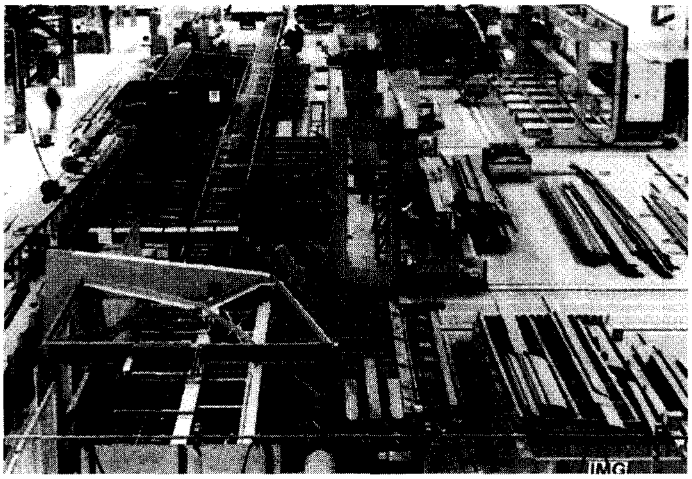

Figure 26.37 Steel Processing Profile Shop

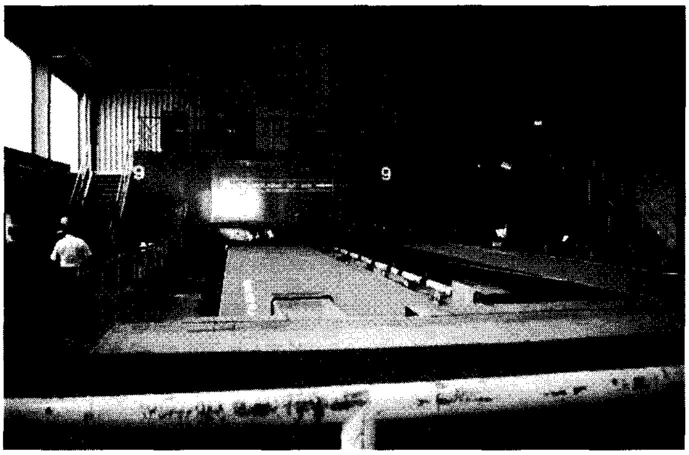

Figure 26.38 Blast and Prime Machine

The plate would be delivered by crane or conveyor to burning machines. For contoured parts or parts with notches and openings the plate would be cut and marked by a *computer numerically controlled plasma or laser cutting and marking machine* (Figures 26.39 and 26.40 respectively).

For rectangular plates used in panels the plate is cut on an oxy-gas or plasma *flame-planning machine.* Sometimes the plates are cut oversize and machined edge milled to the precise shape.

The rectangular plates are joined together into panels by a *one-sided welding machine* at the start of the *flat panel line* (Figure 26.41). The rest of the flat panel line has *workstations* (see Figure 26.21 and Figure 26.42) where the stiffeners (profiles) and web frames are connected to the panel and all the welding completed as the panels move down the line.

Some lines only produce stiffened panels. Others produce sandwich blocks, such as double bottoms or double sides, and even large 3D blocks. In this case there is either a *pit* at the end of the panel/block line, which allows a transporter to drive under the block, or special trolleys with hydraulic lifting jacks (Figure 26.43), and lift it off the panel line tracks by elevating the transporter platform (Figure 26.44).

All of the portable welding machines, as well as other services, are suspended from overhead gantries or pivoting jib cranes, to keep the panels/blocks clear of welding machine cables and service hoses. This aids quick movement of blocks down the line and improves efficiency of use and safety (Figure 26.45).

Some shipyards have robotic welding stations for the egg crate structure (Figure 26.46) and these may be in-line or off line in a special workstation adjacent to the block line.

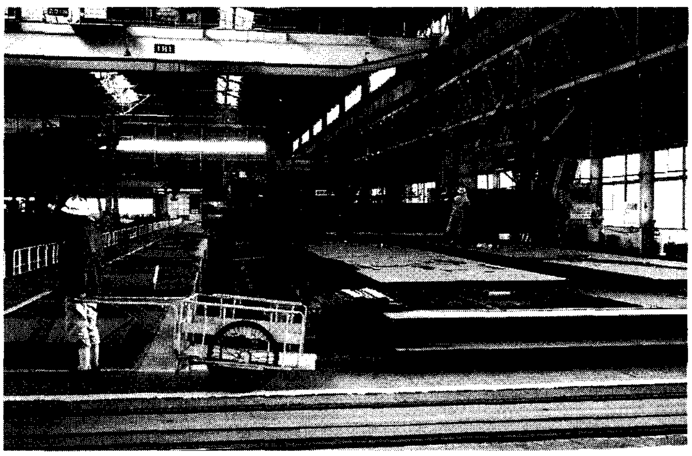

Figure 26.39 Plasma Cutting and Marking Machine

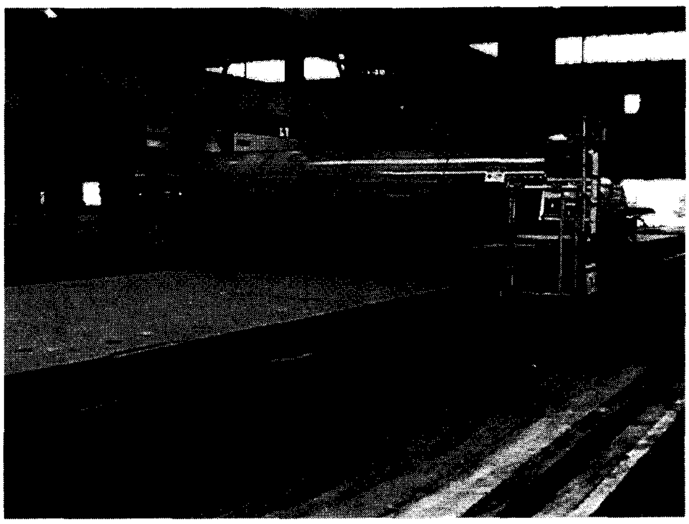

Figure 26.40 Laser Cutting and Marking Machine

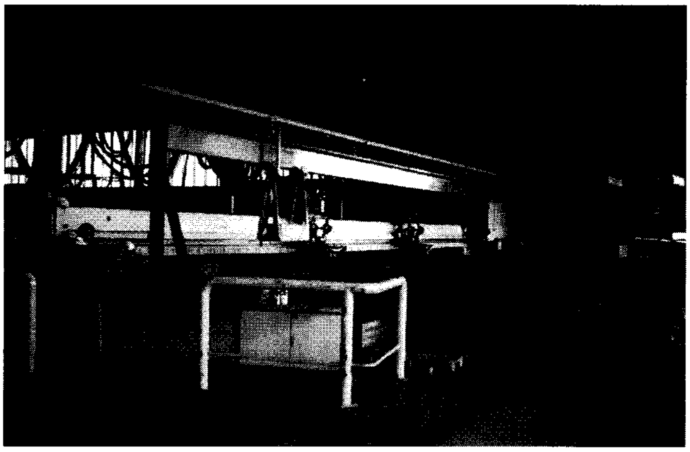

Figure 26.41 Flat Panel Line Start and One-sided Welder

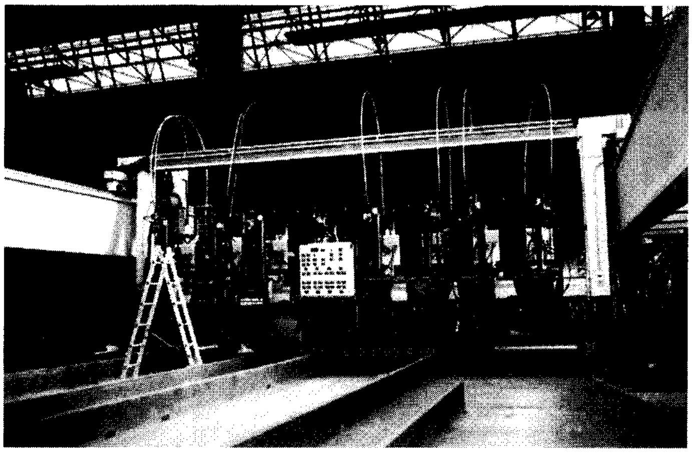

Figure 26.42 Flat Panel Line Workstation: Stiffener Welder

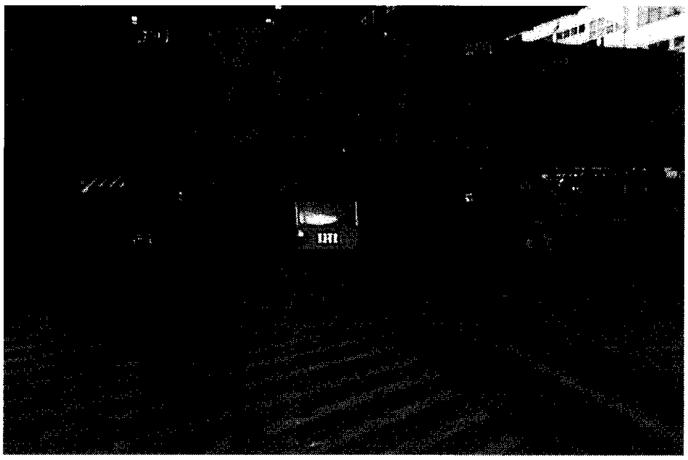

Figure 26.43 Transporter Moving Block from End of Panel/Block Line

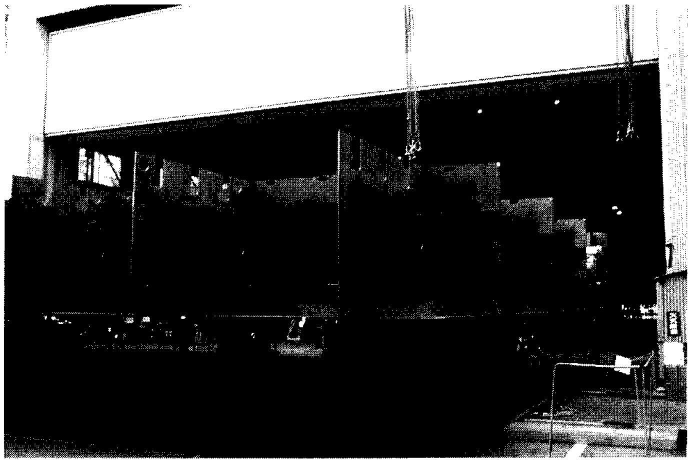

Figure 26.44 Trolley System for Moving Blocks Out of Shop

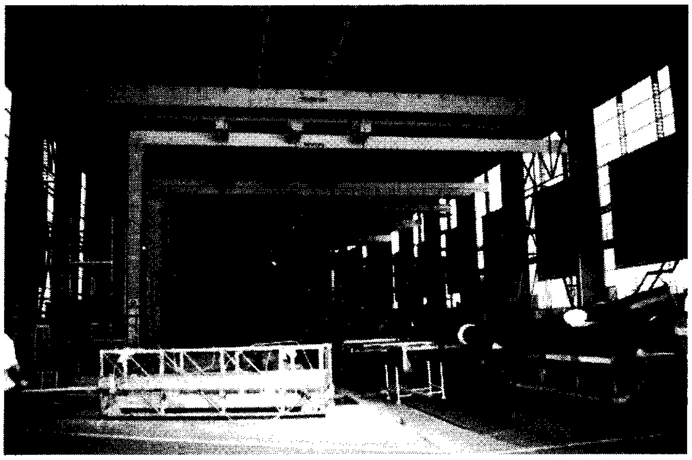

Figure 26.45 Overhead Welding and Service Gantry

Figure 26.46 Egg Crate Welding Robot

In the second bay the profiles when delivered would be fed to a blast and prime machine and then to the storage magazine. The profiles would be automatically fed to a *robotic cutting and marking machine* (Figure 26.47).

They are then delivered to the flat panel line, the sub-assembly line or to the *numerically controlled profile-bending machine* (Figure 26.48).

The rest of the second bay is used to build sub-assemblies (a combination of plate and profile parts). This is accomplished by a *robotic sub-assembly welding line* (Figure 26.49).

In the third bay, plates for curved part of the ship such as the bow and stem, are formed by *large roll machines* (Figure 26.50) or *ring presses* (Figure 26.51) each capable of applying thousands of tons of pressure to shape the plate.

Plates are also shaped using a method called *Line Heat Forming,* (Figure 26.52), which achieves the shaping by ap-

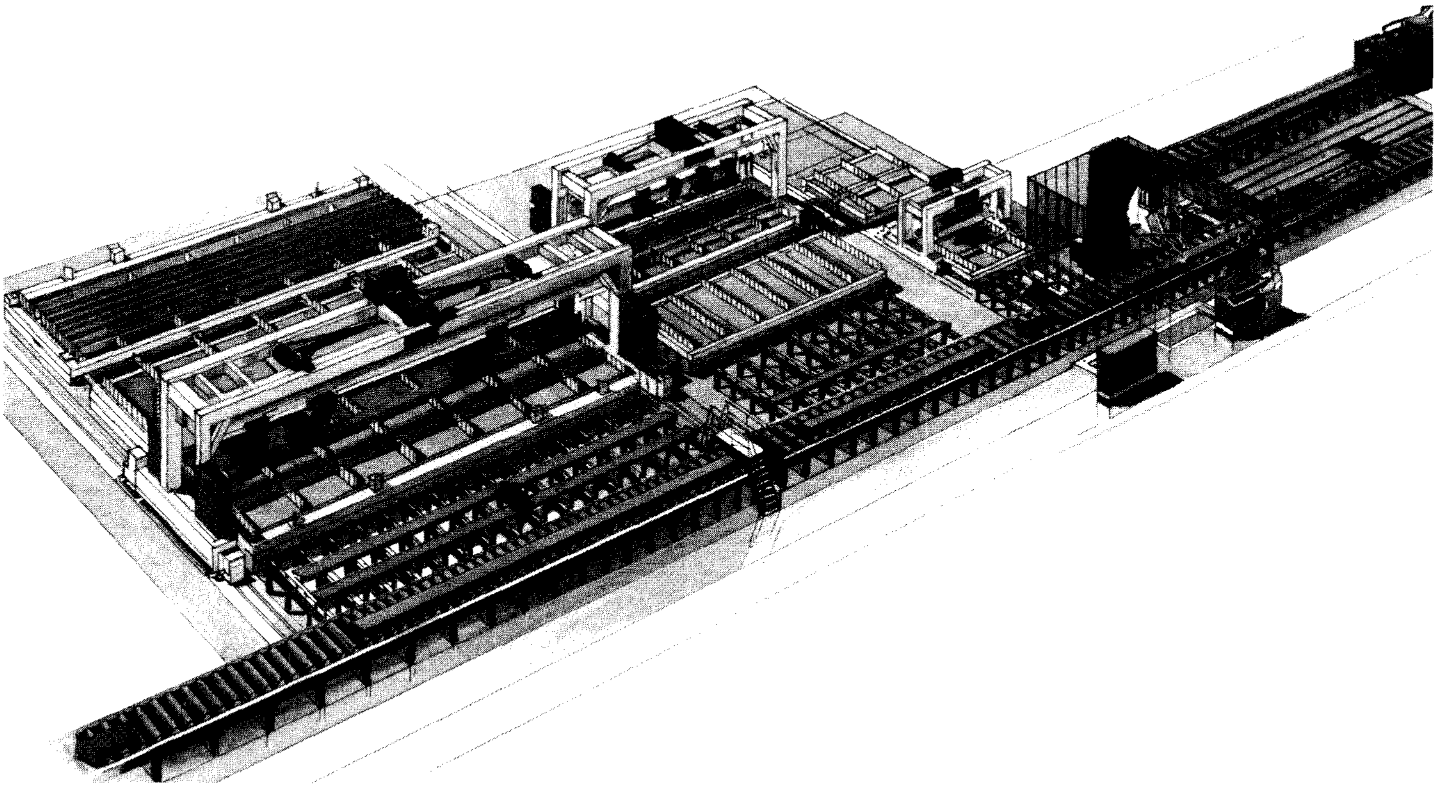

Figure 26.47 Profile Cutting and Marking Robotic Processing Line

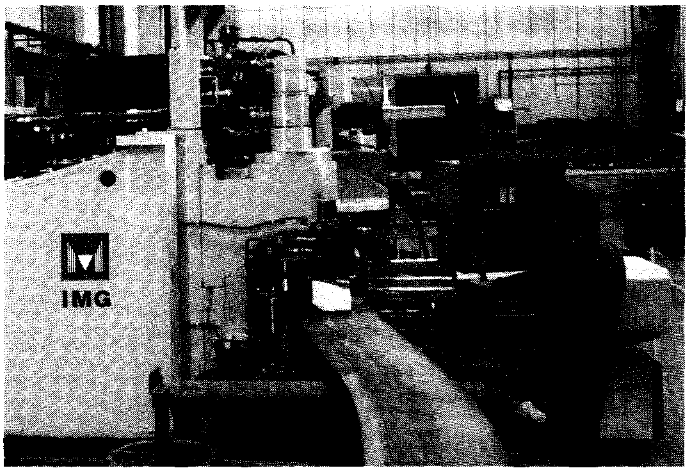

Figure 26.48 CNC Frame Bending Machine

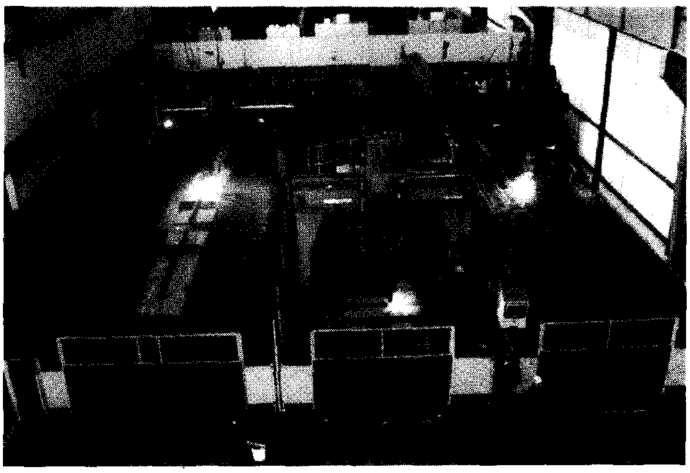

Figure 26.49 Sub-assembly Welding Robot

plying heat locally to predetermined lines on the plate and then quickly cooling by water, which distorts the plate. The shape of the plate is checked by *roll sets.* The shaped plates are placed on a set of pre-positioned *pin-jigs* (Figure 26.53) and welded together.

Then the shaped profiles and web frames are positioned on the curved panel and welded out to form curved blocks. This may be done in fixed workstations or on a moving curved block line (Figure 26.54). The blocks are then cleaned and painted except in the way of the joining butts and seams. They are then advanced outfitted with piping and equipment (Figures 26.55).

While the structure is being processed the pipe is also being processed in the *pipe shop.* The pipe, except the very

Figure 26.52 Line Heat Plate Shaping

Figure 26.50 Plate Rolls

Figure 26.53 Pin-Jigs

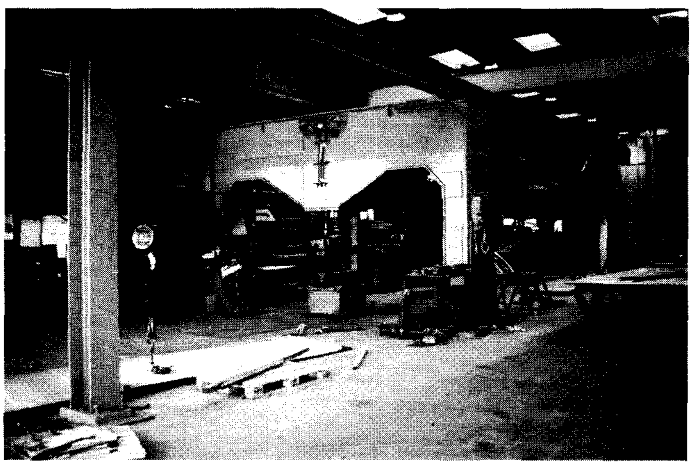

Figure 26.51 Plate Ring Press

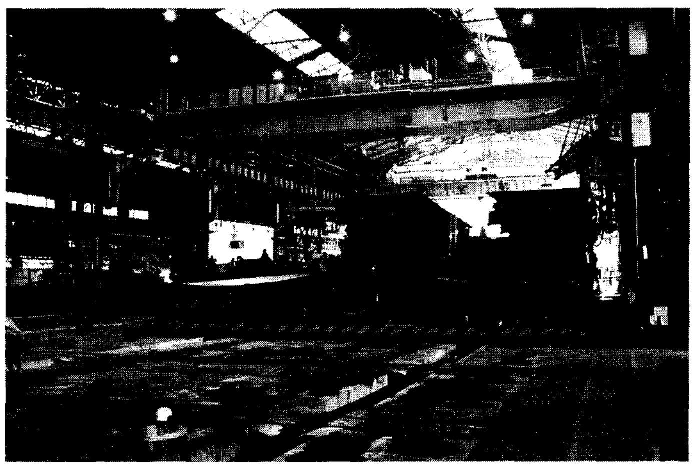

Figure 26.54 Curved Block Line

large or special shaped pieces, will be automatically processed. The pipe is automatically delivered from the *pipe storage magazine* (Figure 26.56) to the *robotic pipe cutting and flanging machine* (Figure 26.57), which can process

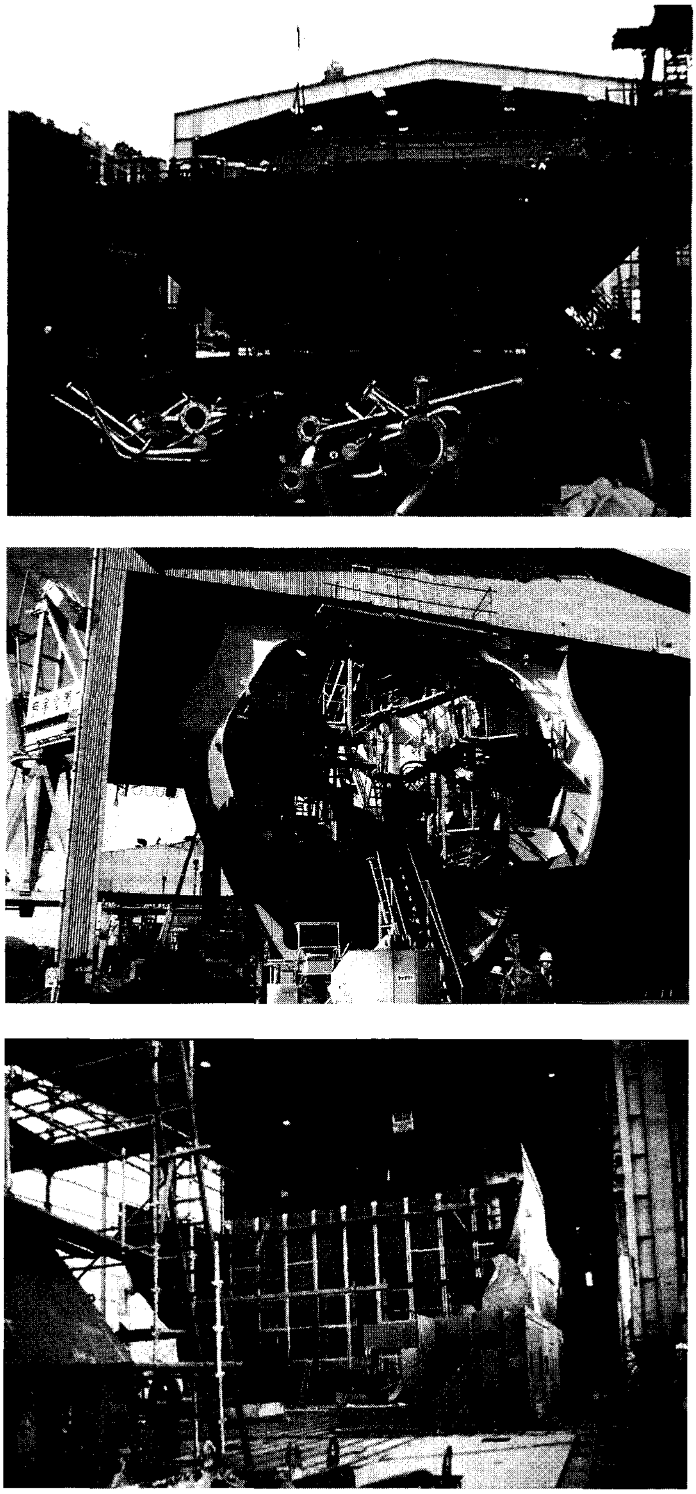

Figure 26.55 Blocks being Advanced Outfitted

pipe up to about 200 mm in diameter. Numerically controlled pipe bending machines (Figure 26.58) are used to bend the pipes into their required shape up to a certain pipe diameter. Above that diameter, pipefittings *(elbows)* are used.

Larger pipe is assembled manually as shown in Figure 26.59. At the end of the pipe shop the pipe pieces are grouped together onto *pallets* (Figure 26.60) for each block or zone to be outfitted and delivered to the outfitting workstations.

The shipyard has other buildings that provide storage space for equipment as it is delivered by the vendors, electrical warehouse and electrical cable assembly. The outfitted blocks are transported to a location adjacent to the drydock, by *multi-wheeled heavy lift transporters* (see Figure 26.31) or *crane(s)*, where two or more are joined together to form *Grand Blocks* (see Figure 26.30). The grand blocks are then erected into the dry dock by large lift capacity *gantry crane* (see Figure 26.7) and joined together.

The propulsion engine is installed into the ship and the deckhouse erected on the hull.

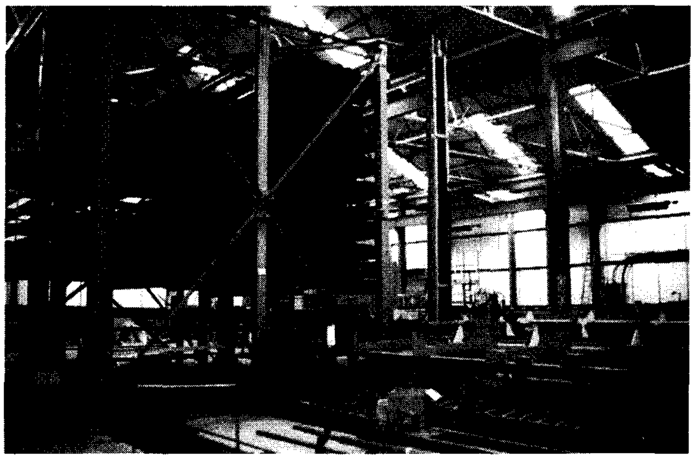

Figure 26.56 Pipe Storage and Delivery Magazine

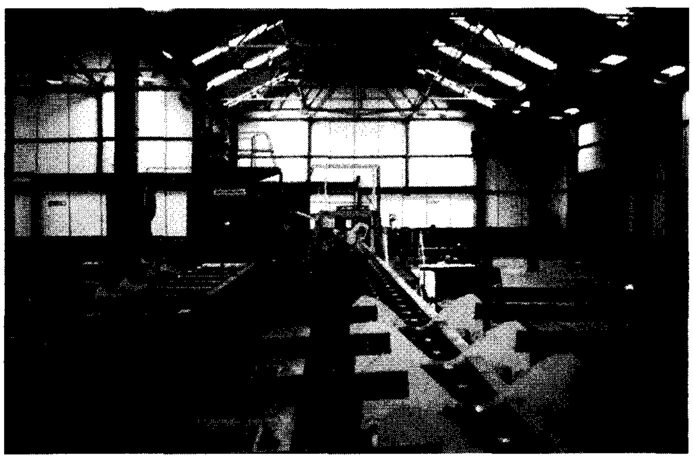

Figure 26.57 Pipe Cutting and Flange Welding Robot

The remaining outfit is then installed and the ship completed, including the final coat of paint. The ship is then launched and moved to the fitting out quay, although today, for commercial ships, very little outfitting remains to be installed at this stage.

Naval ships traditionally have long afloat, outfitting duration's, but even this is reducing in some shipyards by the application of zone outfitting to naval ships. While the testing of the different systems in the ship starts as early as possible, even while the ship is still on the building berth, most of the ship wide, cargo and propulsion systems testing is done once it is floating. The outfitting quay will have equipment and services suitable for the testing that is performed afloat.

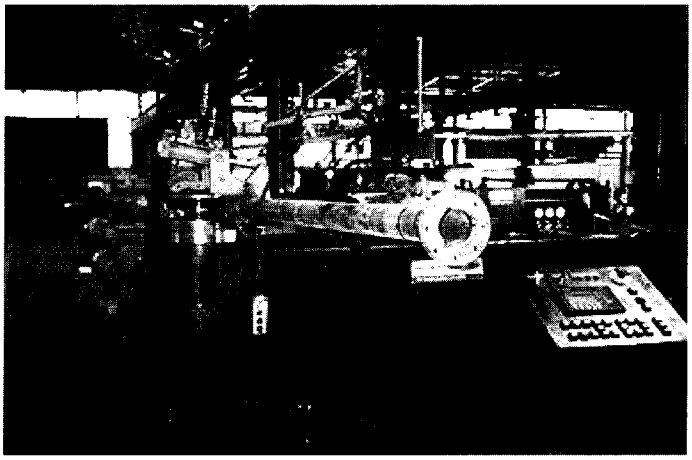

Figure 26.58 Pipe-bending Machine

26.4 SHIPYARD EQUIPMENT

The aim of this section is to provide a detailed breakdown of the major items of equipment to be found in a modern shipbuilding facility. Technical details are provided for each of the items identified. In a modern shipyard the size, capacity and performance of the equipment used varies greatly. In order to arrive at the most important details the information is been organized in the following way:

- identification of the main working areas of a modern shipyard,
- identification of the major items of equipment to be found within each area, and
- important technical characteristics of the equipment items.

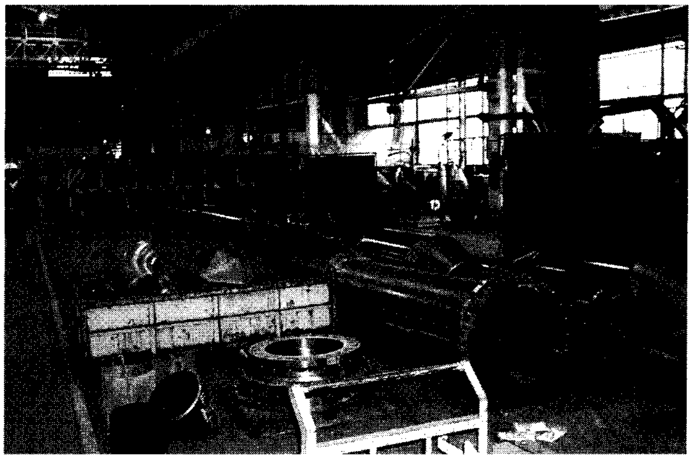

Figure 26.59 Large Pipe Manual Fabrication

Some of the areas identified within the shipyard, such as treatment facilities and flow lines, are now sometimes supplied as integrated systems. In these cases a generalJdescription of the area is given together with some information on individual workstations. Typical equipment specifications for each of these workstations are provided, although from a supplier point of view the overall process area is treated as a single item.

Similarly, at many of the areas identified, there are items of general equipment such as cranes and transport systems for which a general technical specification gives a good idea of typical capacities and performance.

Finally, it is important to note that the details given here are only provided as a guide. The precise definition of the equipment required can only be arrived at when many other variables have been fixed, such as detailed analysis of output in terms of CGT/year and product mix are known together with site layout, construction methods, etc.

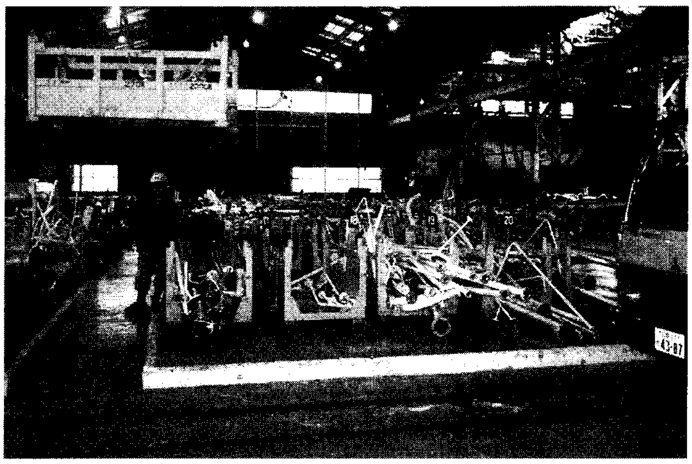

Figure 26.60 Pipes Sorted in *Pallets*

For the purposes of this shipyard equipment description section, the following production areas have been identified as typical of a modem shipyard:

- steel stockyard,
- steel preparation facilities,
- plate cutting,
- profile cutting, forming and welding,
- large panel line,
- double bottom/side panel line,
- small panel line,
- web and component line,
- curved panel line,
- manual fabrication / production area,
- large 3D block production area,
- pipe shop,
- sheet metal shop, and
- paint shop.

Each of these areas has been considered and a list of the major items of equipment compiled along with typical technical details for these items. Some discussion of the area functionality also has been give where this helps in identifying the important technical features.

26.4.1 Shipyard Area Breakdown and Technical Summaries

The main steelwork areas within a typical modem shipyard layout are dealt with in each of the following sub-sections. For each area a description of the function and general arrangement is given and tables are used to summaries the major items of equipment and their relevant technical details.

26.4.1.1 Steel stockyard

The stockyard is normally an open-air area in which plates and stiffeners are stored in piles or racks until required. 'Ite size of the area is dependent on production requirements and delivery intervals. The plates are normally stored horizontally in piles. This area is controlled by a gantry crane which picks the plates up individually, by magnetic crane, and transports them to a buffer zone prior to infeed to the surface treatment line. At this stage they are loaded onto a roller conveyor with a crane or a captivator (Figure 26.61) (semi-automatic, electrically driven vehicle with magnetic yoke to take plates one at a time from buffer zone to roller conveyor infeed of steel preparation line).

Profiles are normally handled in bundles and manually separated and sorted into charges on a transfer table outside the surface treatment line. Alternatively, two sets of transfer tables with bundle pockets can be used in conjunction with a profile sorting crane that can pick up profiles one by one from the open bundles and put them on the roller conveyor. Some shipyards store the profiles in automatic delivery magazines similar to those used for pipe (see Figure 26.53). Table 26.II gives details of a typical stockyard crane.

26.4.1.2 Steel preparation facilities

Plate and profile treatment: The steel treatment facilities are usually supplied as a complete and fully automated unit capable of shot blasting and painting both plates and stiffeners. The system typically has infeed on roller conveyor and can accept plates up to a maximum of 3 m width. Stiffeners can be handled in charges or individually. The major items of equipment within the line are as follows:

- roller conveyors,
- pre-steam cleaners,
- wheelabrator shot basting,
- airless spray paint primer shop, and
- post paint drying.

Plate cutting shop: This area is concerned with the cutting, marking, sorting and distribution of steel plates.

The infeed from the steel treatment line will consist of a variety plate sizes and thickness and can be organized for handling into three categories, 1) less than 0.3 m by 0.3 m-manually, 2) from 0.3 m by 0.3 m to 1.5 m by 1.5 m-picking machine with one or two magnets, and 3) more than 1.5 m by 1.5 m up to 3.0 m by 16.0 m--overhead crane in sorting area.

The cutting shop and sorting area would typically consist of:

- a cutting area with plate buffer and machine loading crane or transfer conveyor for loading plates onto the cutting tables and unloading the cut plate and bringing it to a plate trolley,

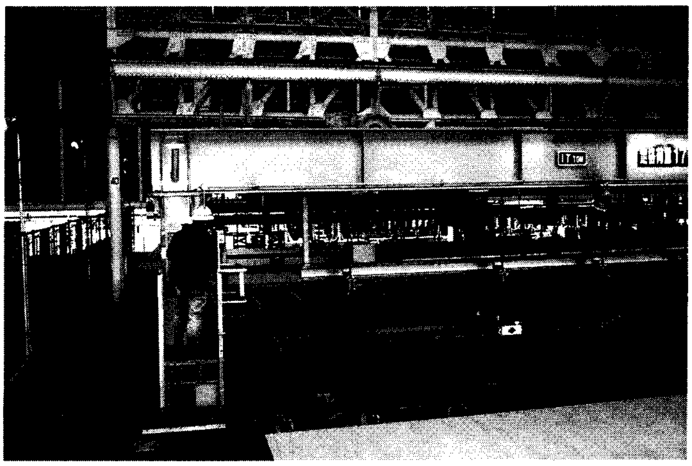

Figure 26.61 Steel Plate Conveying System

- a number of cutting and marking machines: oxy-fuel, and plasma or laser,
- edge milling machine,
- sorting area equipped with picking machine for medium pieces and overhead crane for larger plates, and
- transport system with plate trolley and roller conveyor.

The most important of these elements are:

Cutting and Marking: Cutting equipment can be split into three basic types:

- oxy-fuel,
- plasma, and
- laser (both Nd YAG and CO_2),

At present oxy-fuel and plasma cutting are the more usual types and the important technical features are summarized in the Table 26.III.

The advantages of modem laser equipment are considerable and their use is gaining ground in state of the art shipyards. Table 26.IV gives a comparison of laser verses the older technologies. Laser technology is often thought to be

TABLE 26.II Technical Specifications of Stockyard Crane

Crane Area	*Plates*	*Profiles*	*Profile Sort*
Crane Type	Gantry	Gantry	Gantry
Span Width	40 m	28 m	5 m
Traveling Length	70 m	38 m	25m
Traveling Speed (m/min)	100	16/63	10/40
Trolley Speed (m/min)	40	5/20	10/49
Driver/Hoist	Electric	Electric	Electric
Power Consumption	—	—	40 kW
Pick-up Type	Magnetic yoke	Magnetic yoke/slings	Magnetic yoke
Lift Capacity	18 tonne	10 tonne	2.7 tonne
Lift Height	6 m	6 m	1.2 m
Hoist Speed	1.7/10 m/min	1.7/10 m/min	1/6.3 m/min
Turning of Pick-up	—	—	+/–90°

TABLE 26.III Technical Specification of Cutting Equipment

	Flame Cutting Machines
Operation range	• Width 3.3 m • Length 16.5 m
Procedure	• underwater plasma cutting with injection cutting torch • carrier gas: oxygen or nitrogen alternatively • oxyacetylene cutting on water bath
Operation mode	• setting operation; automatic operation
Kinds of seams	• Plasma: square butt weld and single-V weld for square cuts (torch angle setting + 65 degrees) • Oxyacetylene: square butt weld, Y-weld, single-V weld and double-V weld
Data transmission	• DNC operation; data are typically taken up by a shipbuilding CAM system and transmitted to machine control via cable
Equipment	• underwater tables • plasma welding torches and plasma units • acetylene three-torch units • torches carriages with drive or without drive but linkable • powder or plasma marking units
Precision requirements	• typically, guiding precision of machines accuracy to DIN 8523 minimum requirements
Average Effective Cutting Speeds	• plasma: 1.0 m/min • autogenous cutting: 0.48 m/min

TABLE 26.IV Comparison of Oxy-fuel, Plasma and Laser Cutting

Comparison	*Oxy-Fuel*	*Plasma*	*HTPAC*	CO_2 Laser
Cutting speed (m/min)	0.9–0.6	3.9–1.9	3.4–2.6	2.7–2.0
Roughness (10 point height irregularities)	38–62	50–82	—	45–80
Perpendicularity Tolerence (mm)	0.9–1.1	1.2–1.4	—	0.6–0.7
Kerf Width (mm)	1.4–1.6	3.5–7.0	1.0–2.6	0.5–0.7
Relative Capital Cost ($k)	38	76	—	114
Running Costs (150 sheets of 6mm mild steel, $)	460	880	—	1270
Total Job Costs (150 sheets of 6mm mild steel running, labour and fixed costs, $k)	21.3	21.4	—	21.6

Note: The range of values given here are for 6 to 14 mm thickness mild steel plate.

TABLE 26.V Typical Specification for Edge Milling Machine

Working range	Length	3–16.5 m
	Width	0.8–3.6 m
	Thickness	6–50 mm
Milling unit	DC motor	56 kW
	Rotating speed	80–200 rpm
	Cutter head diameter	500 mm
	Cutting speed	0.3 m/min
	Quick return	25 m/min
Hydraulic power pack	Pump motor	5.5 kW
	Working pressure	140 bar

TABLE 26.VI Typical Specification for Plate Pallet Gantry

Span width	5 m
Height	4.8 m
Traveling length	11.5 m
Traveling speed	16/63 m/min
Lifting capacity	40 tonne
Lifting/lowering speed	0.63/6.3 m/min
Lifting height	1.2 m
Drive/hoist	Electrical or hydraulic
Power consumption	40 kW

the more expensive alternative and, in terms of capital cost. However, in terms of total job cost, which is more of a real world comparison, the costs are very similar to existing methods. The real strength of laser technology is felt down stream in the production process, where the accuracy of cutting greatly reduces the need for green material in blocks and units and low distortion reduces man-hours spent in assembly. For example, it has been estimated that correcting distortion accounts for as much as 25% of man-hours in the shipbuilding process. A recent improvement, high tolerance plasma arc cutting (HTPAC) is said to be able to match the accuracy of laser cutting at reduced cost.

Edge Milling Machine: This piece of equipment would consist of a plate clamping table with alignment and clamp device and a milling unit. T.he control is CNC, Table 26.Y.

Plate Pallet Gantry: The plate pallet gantry would typically transport plates on pallets between the sorting area of the cutting shop to buffer zones at infeed of the panel lines, Table 26. VI.

Trolley With Roller Conveyor: Direct transport link between infeed roller conveyor to plate shop and the working area of the overhead crane working in the sorting area: the details given here are used throughout as -exemplary, Table 26.VII.

Profile Cutting, Forming and Welding: Typically, this area would be dedicated for profile cutting/forming, and T-beam production. From the different production/assembly lines and stations several preparation and tolerances would be derived for prefabricated profiles:

TABLE 26.VII Typical Specification for Roller Conveyor

Load capacity	20 tonne
Trolley length (overall)	16.8 m
Trolley width	4.5 m
Roller width	3.5 m
Roller diameter	0.19 m
Roller spacing	0.85 m
Transport speed trolley	30 m/min
Transport speed roller conveyor	20 m/min
Drive machinery	Electrical
Power consumption	5.6 kW
Power transmission	Cable reel

TABLE 26.VIII Technical Specification for a Typical Bending Line Marker

Traveling length	16 m
Traveling width	1 m
Drives	Electrical, servo controlled with tachos for speed control
Driving principle	Metal core, PUR coated tooth belts
Accuracy	less than 1mm over 10 m
Speed each axis	15 m/min
Marking method	plasma (argon gas)
Process speed	10 m/min

- all kinds of end shape preparation,
- cutting of drain holes,
- production of profiles with small tolerances both in cross section and for side and edge camber compared to standard steel mill production,
- edge beveling,
- remove paint in welding zones-abrasive paper/disc,
- marking of bending and reference lines,
- **ID** marking of components,
- straightening and bending of profiles,
- the prefabricated profiles would be stored on pallets according to order and orientation required from different production lines, and
- the profile shop must also include some manual workstations for special requirements, repaint work. grinding and cutting to short pieces ..

Items of equipment in this area would include:

- transfer tables,
- turning device,
- roller conveyors,
- CNC bending line marker,
- edge cleaning machine,
- cutting, length measuring system and marking equipment,
- edge milling machine,
- chain conveyor,
- picking crane,
- automatic beam welding machine,
- sorting crane,
- profile measuring system,
- profile bending machine, and
- transport trolleys.

The technical specifications of the most important of these items are covered in the following sections.

CNC bending line marker: The CNC bending line marker would be located at the beginning of a profile cutting line. It would consist of a marking device for marking of bending lines and reference lines for web mounting and a profile clamping mechanism. When a profile has been loaded onto the clamping mechanism, it is pressed with the flange side against the fixed part of the clamp side, which serves as a reference line for the marking. This operation also serves to straighten the profile before marking.

Bending line markers are usually CNC-controlled operating automatically in DNC mode, so that constant attention is not required from an operator, Table 26.VIII.

Cutting, length me«suring trolley and marking equipment: Profile length measuring, marking and cutting in a modem facility is likely to be a highly automated process and would be set out as a material flow line. Typically, the process will employ an industrial robot which has been optimized for shipbuilding profiles, with cutting torch, marking torch and profile measuring sensor fixed to the robot arm, thus avoiding tool changes. Sensing equipment means that the pre-defined cutting shapes can be executed despite dimensional deviations in the profiles. The items of equipment at this workstation would include:

- roller conveyor equipped with clamping device,
- industrial robot,
- robot controller,
- 3-D sensing system,
- oxy-fuel of plasma cutting equipment, and
- plasma marking torch

Edge Milling Machine: The edge-milling machine in this area would be designed to chamfer cut edges of both web- and flange plates and would usually have only one working direction. Infeed to this machine would be by roller conveyor, Table 26.IX.

Picking Crane: The picking crane would have different tasks to perform regarding the infeed of plates. It would load/unload the roller conveyor for the milling machine and put web and/or flanges in intermediate storage.

Typically, working cycles can be manual or semi-automatic, and to be able to load big web plates (1.0-2.5 m) the picking crane would be equipped with a special mechanical yoke, Table 26.x.

Automatic Built-up Profile Welding: Automatic built-up profile *(beam)* welding machines are manufactured as complete units by a number of suppliers but the following basic details are typical. The beams are welded with the web plate in vertical position and the flange member in horizontal position when fed through the machine. The machines are designed for the production of 1- and T-shaped beams of maximum size in the range: height = 2.5 m; width = 0.8 m. Other important features include:

- welding method is usually submerged-arc welding (SAW),
- straightening of the flanges in order to counteract the *Pull-Back* is part of the machine, and
- the machine is equipped with automatically operated screws, which follow the beam height in steps, in order to weld beams of tapered type.

Typically a machine would comprise the following basic units:

- basic frame,
- flange and web centering devices,)
- feeding device,
- flange straightening unit,
- control panel,
- flux deposit and recovery units,
- hydraulic power unit,
- welding contact unit suspensions, and
- welding equipment.

Sorting Crane: There will be a number of sorting cranes within the profile processing area. For example, a task for a sorting crane would be to pick up profiles from the outlet roller conveyor after the welding machine and to put them onto the cooling table, and after cooling to transport the welded beams onto the measuring device. When profiles are found straight, the sorting crane places the profiles onto pallets. To be able to put down the profiles correctly in pallets, the sorting crane would have to be equipped with a magnetic yoke that can rotate +/- 180 degrees (horizontally) and the magnets themselves to be able to turn through 90 degrees. The sorting crane would also be able to lift one full pallet of profiles and place it anywhl.;rein the sorting area, Table 26.xI.

Profile Bending Machine: As with automatic profile welding machines, profile bending machines are manufactured by a number of suppliers. The following details give an in-

TABLE 26.IX Technical Specifications of Edge Milling Machine

Number of milling units	5
Power consumption for each milling unit	4 kW
Number of brush units	1
Power consumption for brush unit	3 kW
Number of feeder rollers	2 Pairs
Number of scrap containers	2
Speed by milling/brushing	4–6 m/min
Transport speed	30 m/min
Minimum width of profile	100 mm
Maximum width of profile	1000 mm
Thickness	11–25 mm

TABLE 26.X Technical Specifications of a Picking Crane

Specification	Span width	17.5 m
	Traveling speed	40/10 m/min
	Drive/hoist	Electrical
	Power consumption	40 kW
	Power feeding	Loop cable
Crane runaway	Height of top rail	4.35 m
	Length of rail	27 m
	Traveling length	23 m
Magnetic yoke	Number of magnets	6 off
	Lifting capacity (each)	500 kg
	Lifting capacity (total)	2700 kg
	Lifting height	1.5 m
	Hoist speed	6.3/1 m/min
	Battery backup	20 min
	Turning of magnets	0/+90 degrees

TABLE 26.XI Technical Specifications of a Typical Sorting Crane

Specification	Span width	17.5 m
	Traveling speed longitudinal	40/10 m/min
	Traveling speed transverse	20/5 m/min
	Drive/hoist	Electrical
	Power consumption	40 kW
	Power feeding	Loop cable
Crane runaway	Height of top rail	4.9 m
	Length of rail	27 m
	Traveling length	23 m
Magnetic yoke	Number of magnets	6 off
	Lifting capacity (each)	700 kg
	Lifting capacity (total)	4200 kg
	Lifting height	2.0 m
	Hoist speed	4.0/0.65 m/min
	Battery backup	20 min
	Turning of yoke (horizontal)	+/- 180 degrees
	Turning of magnets	0/+90 degrees
	Number of hooks for pallet	4 off
	Lifting capacity for pallet	12 tonne

dication of typical technical specifications (see Figure 26.48).

The modern profile-bending machine is a 4-way bending and straightening press and this means that the profiles can be completely finished in one set-up saving both handling and working time. The main purpose of the machine is bending and straightening of ship-profiles horizontally both + and - direction, as well as vertically, again in both directions. The machine could comprise the following elements:

- a quality tested rolled plate frame,
- 2 profile clamps attached to the frame by 4 hydraulic cylinders,
- the main bending or straightening beam running in guides fitted to the base,
- at the front end the main beam has two counter acting hydraulic cylinders for vertical bending and 2 web supports for horizontal bending, amI
- pneumatic cylinders for disconnecting the 2 web supports when bending vertically.

This type of machij1ery can usually be operated in manual, semi-automatic or fully automatic modes, Table 26.xU.

TABLE 26.XII Technical Specification for a Typical Profile Bending Machine

Max. press power, horizontally	640 tonne
Max. stroke length forward direction (+)	300 mm
Max. stroke length backward direction (-)	200 mm
Press speed horizontally at max 40% load	17 mm/sec
Press speed horizontally at max 100% load	6.1 mm/sec
Press power vertically in both directions, max	100 tonne
Stroke length vertically	+/- 75 mm
Vertically bending of 100% load	17 mm/sec
Max. distance between profile holders (side arms)	3000 mm
Min. distance between profile holders (side arms)	1500 mm
Lateral feeding of material speed	50 mm/sec
Changing of clamp distance speed	100 mm/sec
Profile holder power	125 tonne
Motor power, total installed	50 Hp
Net weight, approx.	45 tonne
Max. working pressure, approx	30 MPa

26.4.1.3 Web and component sub-assembly line

The web and component line is for the manufacturing of plates with stiffeners and is usually supplied as a complete *turnkey* system. The units are assembled, tack welded and completely robot welded within the line (Figure 26.62).

The different sub-systems incorporated in the line, forming the total production system, are as follows:

- roller conveyor,
- roller conveyor with cross~transfer,
- transversal conveyor,
- roller conveyor (parking position with magnetic clamping),
- work table,
- mobile stiffener gantry,
- robot welding gantry,
- electric control system, floor equipment, and
- rails and accessories.

The stiffener mounting gantry is used to collect profiles from the pallets positioned aside the line, position them on the plate, and to clamp the profile to the panel during the tack welding work (Figure 26.63). The main components of the system are the gantry, a clamping trolley and the welding equipment. The gantry itself is typically semi-portal with 7 m span, electrically operated machinery and traveling speed 0-20 m/min. The clamping trolley is electrically

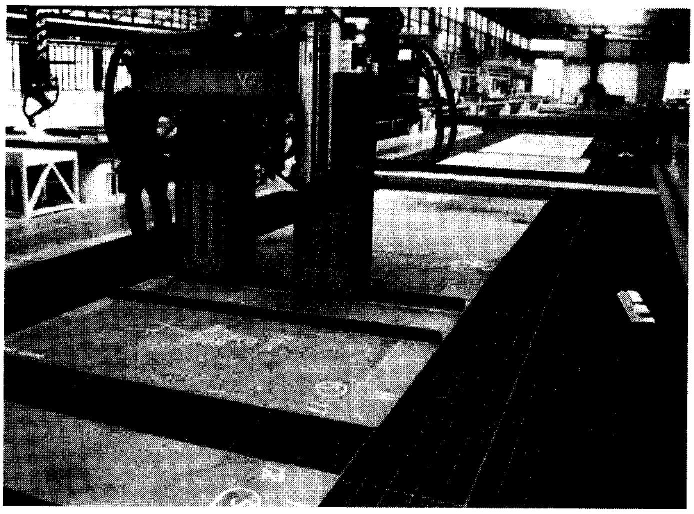

Figure 26.62 Robotic Stiffener Fitting and Tack Welding Workstation

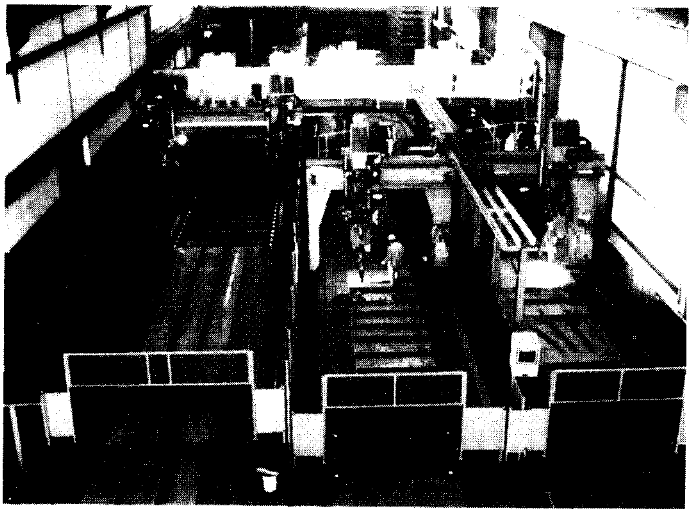

Figure 26.63 Robot Welding Workstations

operated with traveling speed of 2.5/1 0 mlmin and hydraulic lift operation. The total clamping force would be in the region of 15000 kP. The welding equipment used for tacking is MIG/MAG. The robot-welding gantry (Figure 26.63) is located for welding the web and component structures. The specifications of the gantry would be similar to those of the stiffener-mounting gantry. The robots are equipped with welding equipment, seam finding and tracking sensors and an automatic torch clean system. The whole workstation is controlled from a central console equipped with industrial computers.

26.4.1.4 Small raanelline

Small panel lines are supplied as complete production systems by a number of manufacturers. The main components of a typical small panel line are as follows:

- roller table for plate pallets,
- safety stop,
- lifting frame,
- hydraulic magnetic manipulator,
- chain magnet manipulator,
- liftable guide,
- swivel roller,
- panel rotation wheel,
- water table,
- conveying chain,
- steel floor with grid,
- steel deck,
- electronically controlled floor equipment,
- one-sided welding station,
- cutting machine,
- plate picking gantry,
- workshop gantry,
- mobile stiffener gantry,
- robot welding gantry,
- service gantry, and
- rails and accessories.

Most of the elements of the system would have similar specification to areas in the shipyard discussed previously, but there are several features that need to be detailed explicitly.

The roller table system consists of a number of separate tables, each tables is mounted on rollers and has its own motor drive system and is used to transport the plate pallet to the buffer area in front of the panel line. The safety stops are simple brackets fixed to the floor and will prevent the plate/panel from derailing at both ends of the line.

The one sided welding station would be typically used 3-wire submerged arc welding equipment.

The perimeter-cutting machine has to fulfill a variety of functional requirements: '

- shot blasting of areas for mounting and welding of profiles, webs and bulkheads,
- marking of locations of units to be mounted, reference lines for profiles if required and identification marking,
- contour cutting of plate and cutting of holes or shapes or nested small parts-with Plasma Cutting,
- contour cutting of panels and cutting of holes or shapes, including of edge preparation for butt welding of panel to panel and for other connections in the further volume section mounting process-with Gas (Autogen-) Cutting,
- automatic operation of the machine, controlled by CNC, and
- working upon a water cutting table and integrated into the transport equipment of this table and of the line.

The service gantry carries welding units, and serves as an efficient and time saving tool for final welding. The welding sets with wire feeders and hoses for fume extraction are arranged on the gantry.

26.4.1.5 Large panel line (including twin skin [SANDWICH] line)

A large panel line for *single skin* and the *twin skin* (sandwich) lines contain essentially the same items of equipment:

Floor equipment:
- swivel rollers,
- lifting frame with rollers,
- magnetic manipulators,
- hydraulic manipulators,
- panel rotation wheels,
- liftable aligning brackets,
- fixed path rollers with guide iron,
- welding floor wlliftable rollers, and
- welding floor.

Other equipment:
- plate picking crane,
- one-sided welding station,
- cutting machine with gas cutting, Vacu blast, plasma marking and laser positioning equipment,
- mobile stiffener trolley,
- automatic stiffener portal with magnetic damping, submerged arc welding tractors for fillet welding (Figure 26.64),
- service gantry,
- UHL transport train, web-mounting fixture,
- turnover beam, and
- load out beams.

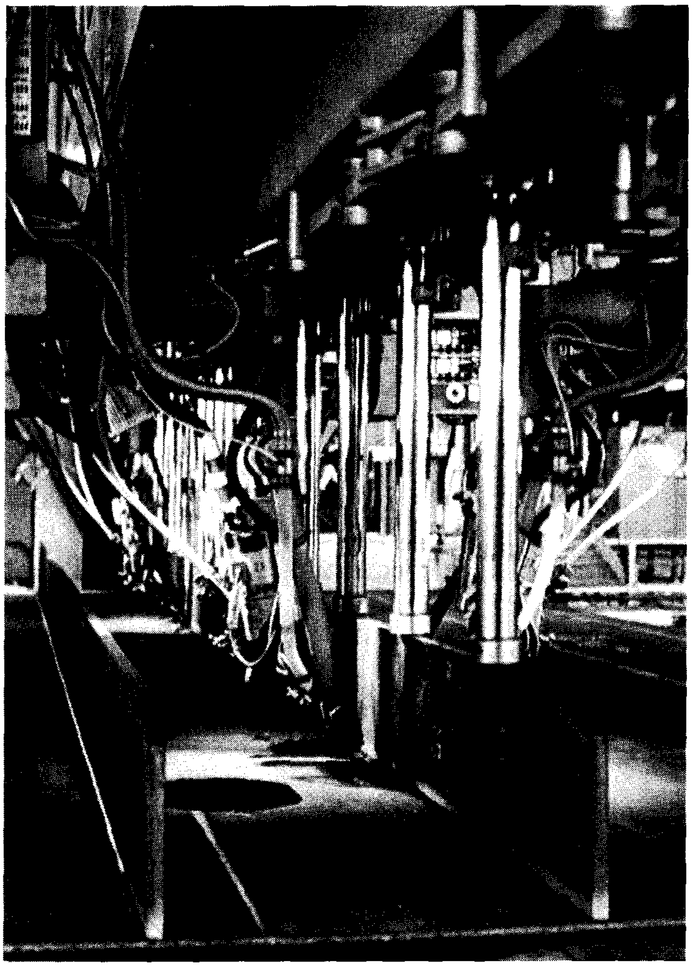

Figure 26.64 Flat Panel Line Stiffener Welding Workstation Showing Hydraulic Rams

Panels from the large panel line will be transported to the double bottom line by means of transport wheels and rollers. Egg-boxes from the egg-box mounting statim will be lifted on to the panel by means of overhead crane.

26.4.1.6 Curved panel line

The curved panel line is arranged as a flow line for manufacturing curved panels and sections and functions as one fabrication technology unit. The various types of equipment integrated in the line may be summaries as follows:

- pin jig,
- drive arrangement for pin jig,
- tilt table station,
- floor equipment,
- jib crane welding equipment,
- mobile stiffener gantry,
- fillet welding service gantry, and
- rail and accessories for gantries.

There are a number of possible approaches to the automation of this type of line but one method is to use a set of moveable pin jig' frames (see Figure 26.52). Typically, the flow line would consist of say six workstations, where six identical pin jig frames are used, one for each station. A pin jig consists of a rigid steel frame of 11 m by 16 m within which aIm by 1 m matrix manually adjustable pins is fixed, the height of these pins being determined for the operators by a list for CAD.

At *station number* 1, overhead cranes lift plates onto the jig, adjusted together and tack welded using welding equipment mounted on ajib crane next to the workstation. When all the plates of the panel have been mounted, ceramic or fiberglass backing is mounted on the underside of the panel, for the submerged arc (welding tractor) and MIG/MAG respectively. Clamping tools (magnets etc.) for backing arrangement are also required.

At *station number* 2 there may be a *tilting table*, as shown in Figure 26.65, which allows the use of automatic welding for the plate butts and seams. When the various stations are ready with its work on the panels, the line is prepared for transport.

The curved panel on *station number* 6 has to be lifted onto a wheel-loader at the end of the building by means of one or two of the overhead cranes. The empty pinjig is then lifted onto another transport vehicle for transportation to the front of the line while the other jigs are moved forward by one station. A gantry supporting one or more submerged arc welding tractors carries out fillet welding of stiffeners.

26.4.1.7 Painting

The painting area consists of the following elements:

- blasting and cleaning cabins,
- paint spraying cabins,
- semi-automatic and/or semi-mechanized blasting and paint -spraying technology,
- paint store,
- tool carriers,
- feeding and transporting by pallets,
- intermediate storage areas for sectionslblocks, and
- transportation of the sectionslblocks by trolleys to the final assembly zone.

The size of the various process cabins is obviously dependent on the unit size being treated, but a typical size would be able to accommodate a 12 m by 12 m by 10 m block. Transport ofblocks into these areas is via low-loading wheeled cradles, or craned in if the paint facility has a removable roof.

Blast cleaning is via metallic or non-metallic compressed air systems. If a blast material recovery system is installed then the more expensive metallic grit or shot can be used and the whole operation is then cleaner .•

Paint application is by airless spray in coats of typically 150 microns. The storage and handling of paint can be improved greatly by the introduction of container bulk storage due to the reduction in environmental costs.

Mobile scaffolds and cherry pickers provide access to the blocks.

26.4.1.8 Block assembly

The assembly sites for large blocks and superstructures usually are performed in fixed workstations, as shown in Figure 26.66, which consists of steel girder let into the shop floor, arranged with a distance to one another of 6 m in longitudinal and cross direction. The area might consist of a craned length of say 200 m with manufacture on the grating of the following volume section:

- bilge 3D blocks,
- side boxes,

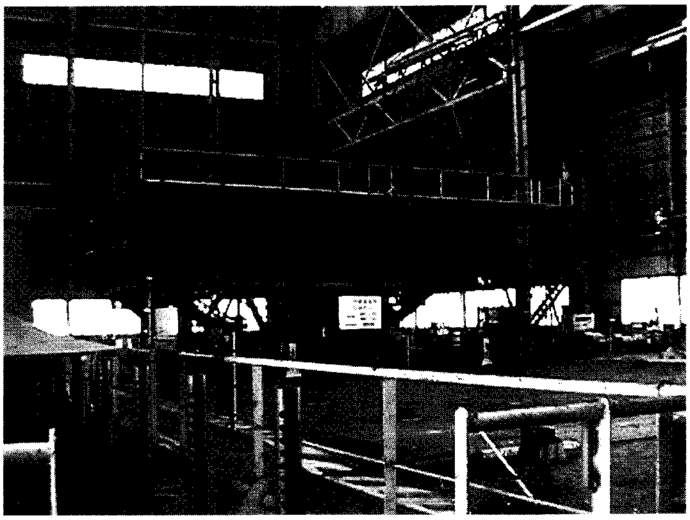

Figure 26.65 Curved Panel Welding Tilting Table

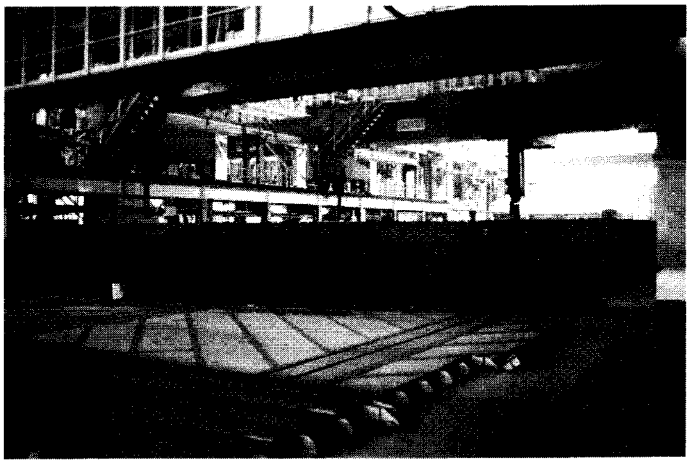

Figure 26.66 Block Assembly Fixed Workstation

- tanks,
- side shell blocks,
- superstructure partial sections,
- foreship partial sections, and
- aftship partial sections.

Some Shipyards build the blocks on an extension of their panel line.

The main transport and other requirements of these assembly areas can be defined with reference to their function, as follows:

- production for double shells (bottom shells, shell plating, bulkhead sections),
- production in working zones with integrated turning deVIce,
- production of circular sections and fore ship sections by mounting supports which can be equipped with other devices, and

- mounting supports, adjustable supports and other devices are fastened to the floor.

For larger blocks:

- assembly of stern and bow blocks, circular sections and superstructures as well as outfitting work in mounting areas with variable sizes,
- assembly of the complete stern (large grand block) including engine room and partial outfitting on a special stern assembly zone and loaded into the building dock by elevator (see Figure 26.32) or floating heavy lift crane (up to 3000 tonnes),
- the mounting support in the assembly zone consists of pillars embedded into the floor and other mounting platform and adjustable supports,
- use of mobile scaffolds in the assembly zones,
- stern-mounting area where larger blocks are transported in transverse direction on keel block supports to the final assembly area,
- the transport of all other blocks from the grand block mounting area to the final assembly area is done by either an 800 tonne lift gantry crane(s) (Figure 26.67), or by elevators or transporters. Figure 26.68 shows the dimensions of gantry cranes for a 1 million tonne Dwt building dock,
- the final assembly of the hull is done on keel block supports by joining the blocks/grand blocks,
- rail system with wheeled cradle for the keel block support system,
- intermediate store and buffer zone for engines and other components, and
- after completing of the hull and final painting in the final preservation in the final assembly zone the ship is shifted to the launching system by means of the cradles.

The main items of equipment are the shop cranes and their capacity and arrangement obviously depend on block size and throughput, but typical requirements might be:

- 1 full gantry crane 80110 tonne, track gauge 40 m to 50 m, lifting height above the floor approximately 30 m to 40m;
- 1 full gantry crane 2 times 40 tonne, track gauge 40 m to 50 m, lifting height above the floor of approximately 30 m to 40 m;
- 2 full gantry cranes with rigid rotating jib 12 tonne, track gauge 40 m to 50 m, lifting height above floor 40 m to 50 m, jib radius 40 m;
- gantry crane 1 times 400 tonne, 2 times 320 tonne, track gauge 90 m to 100 m, lifting height above the floor approximately 50 m.

Figure 26.67 Building Dock Gantry Cranes

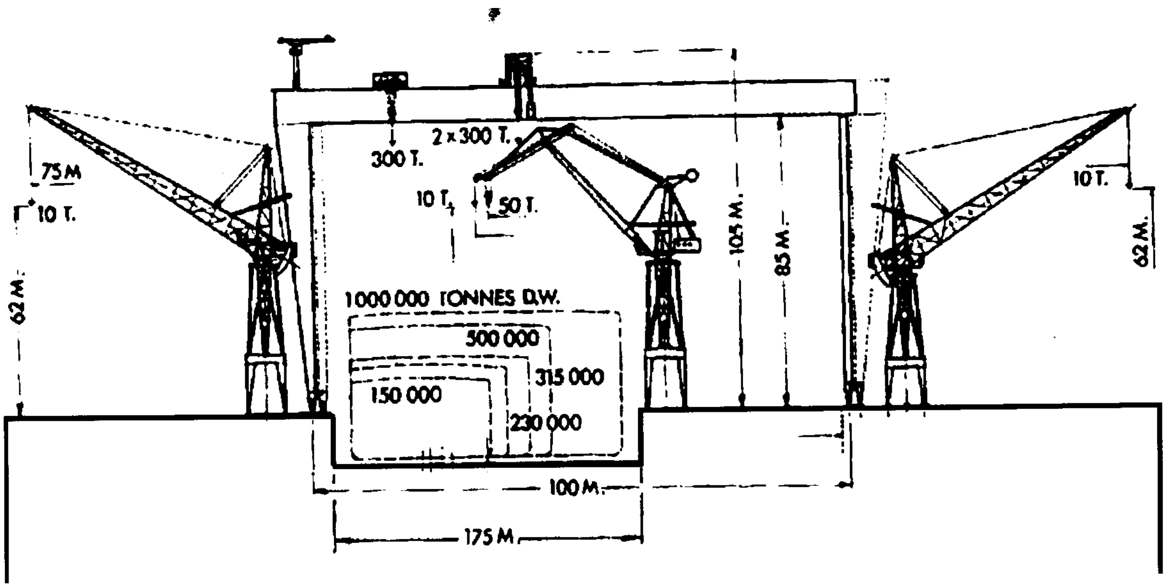

Figure 26.68 Dimensions for a One Million Tonne DWT Building Dock Gantry and Whirley Cranes

TABLE 26.XIII Typical Shipyard Characteristics

	Japan 1963[a]	*Japan 1972*[b]	*Korea 1980*[a]	*Korea 1981*[b]	*Europe 1996*[a]	*Europe 1998*[b]	*USA 1999*[a]	*USA 1962*[b]
Product Range at Shipyard:								
Commercial	LNG, Container	Bulk Carriers, VLCC	VLCC, LNG/LPG carrier, car carrier, bulk carrier, FPSO, container, ferries	VLCC, LNG/LPG carrier, bulk carrier, container ship, car carrier, shuttle tankers, passenger/car ferries	Container, reefer, RO-RO, car carrier, ferries	Passenger, container, chemical tanker, product tanker, multipurpose cargo	Container, tanker	—
Naval	Outfitting Destroyers	—	—	Destroyers, patrol craft and submarines	—	—	—	Amphibious Ships, Destroyers
Total Plant Area (m^2)	833 000	1 500 000	3 300 000	4 200 000	240 000	320 000	—	—
Covered Shop Area (m^2)	454 541	421 801	—	350 000	140 000	240 000	—	—
Number of Building Berths/Size:								
Inclined Ways	2 324×56m	—	—	—	—	—	—	—
Drydocks	3 375×56×14m Building, 1 350×56×14m Repair	2 990×100×14.5m Building, 400×100×14.5m Repair	640×97.5m, 390×65m and 283×46m	530×131m and 350×81m	—	1 340×67×12m	—	—
Level Land	277×38.8×12.3m Repair	—	—	—	1 230 × 32.5 m Synchrolift Launch	—	—	500×32.5 m Floating Dock Launch
Building Berth Cranes	*Drydock* 2 300 tonne gantry cranes 2 150 tonne jib cranes *Inclined Ways* 2 150 tonne gantry cranes	2 600 tonne gantry cranes 2 50 tonne jib cranes 1 35 tonne jib crane 1 30 tonne tower crane 2 10 ton tower cranes	**Drydock 1** 1 200 tonne gantry crane 2 100 tonne Drydock 2 2 250 tonne gantry cranes 1 200 tonne Drydock 3 2 450 tonne gantry cranes	Drydock 1 1 900 tonne gantry crane 2 200 tonne jib cranes 4 50 tonne jib cranes *Drydock 2* 1 450 tonne gantry crane 4 60 tonne tower cranes	*Building Hall* 1 800 tonne gantry cranes 2 150 tonne gantry cranes	*Building Hall* 1 800 tonne gantry cranes 3 50 tonne jib cranes	*Building Dock* 1 1000tonne gantry crane 2 100 tonne	*Erection Berth* 1 900 tonne gantry crane 4 250 tonne jib cranes
Throughput per year:								
CGT/GT	300 000/600 000	700 000/1 300 000	950 000/1 800 000	1 100 000/1 900 000	120 000 /180 000	180 000/1 240 000	100 000/120 000	500 000/60 000
Tonnes of Steel	100 000	200 000	560 000	600 000	70 000	100 000	50 000	50 000
Number of ships	7 to 8	8 to 12	30	35	6 to 8	6 to 8	3	1
Number of Pipe Pcs	200 000	—	213 000	—	—	—	—	—
Maximum size of erected block	Naval ships 60 tonne blocks.	40×30m and 600 tonnes	Drydock 1, 350 tonne Drydock 2, 550 tonne Drydock 3, 900 tonne	Drydock 1, 800 tonne Drydock 2, 400 tonne	20×32.5/350 tonnes	40×30m/750 tonnes	20×32.5/900 tonnes	40×32.5/800 tonnes
Blocks/Grand Block Construction	—	Construct GB for engine room in special Grand Assembly & Outfitting Shop. Shop has movable roof and blocks up to 1000 tonne are erected using both gantry cranes.	—	—	Construct GB for engine room alongside at head of berth and slide it sideways on rollers into position. Blocks by gantry crane	Blocks moved to dock apron by multi-wheeled transporter	Blocks moved to dock apron by multi-wheeled transporter	—
Movement of Blocks/Grand Blocks around the yard/ to the building berth?	—	By cranes and 600 and 300 tonne multi wheel trailers with 0.8m height adjustment and 2 directional movement.	150, 200, 300, 400, and 500 tonne transporters are used to transport blocks to pre-erection area and painting cells. Gantry cranes are used to erect grand blocks in drydocks.	—	—	By crane and 300 tonne multi -wheel transporters. Transporters can be electronically integrated (3) for large moves	300 tonne transporters are used to transport blocks to pre-erection area and painting cells. Gantry crane is used to erect grand blocks in drydocks.	Extensive roller movement system used to move blocks down the process lanes ending up as GB, which are moved into position on the berth.

a. Date constructed. *b. Date rebuilt.*

26.4.1.9 Pipe processing

A modern shipyard would usually be equipped with a fully automated pipe shop. One of the most important features of these modern facilities the introduction of the *flange welding before bending* technology, which allows pipes to be handled automatically and makes cold bending the final workstation. The main areas within the pipe shop can be summarized as follows:

- *Storage*—pipe silo is a magazine with automatic pipe loading and retrieval (See Figure 26.53).
- *Grinding and shot blasting*—end preparation for welding and blasting internally and externally
- *Cutting and labeling*—cutting to length by special saws or plasma with automatic length measuring devices controlled by DNC. Thermal (oxy/plasma) cutting by a CNC pipe-cutting machine has the advantage when processing larger diameter pipes, cutting of holes, and contour cutting. Automatic labeling of pipes is usually combined with the cutting station.
- *Beveling*—to ensure a constant land around the entire pipe circumference for satisfactory butt welding
- *Flanging*—joining and welding in one station, plasma welding for neck flanges etc. with fully automatic operating cycles (see Figure 26.56). Can also do *flange forming* in which the flange is put on and the pipe is slip formed.
- *Coating*—painting in the processing line for pipes, which have been previously shot, blasted.
- *Bending*—pipe processing requires cold bending machines suitable for accurate to size bending of flanged and unflanged pipes. Modern CNC bending machines (see Figure 26.57) for flanged pipes can be equipped with stack tools and tool changing devices in order to shorten set-up times. Can also bend using induction heating.
- *Extrusion* equipment.
- *Manual fabrication tables and jigs.*

26.4.1.10 Sheet metal processing

The sheet metal working area would contain machinery to be found in all parts of a shipyard such as cranes, transport systems and cutting equipment. However, the main items of sheet metal working machinery of interest here are those directly concerned with mechanical cutting and forming. These items can be summarized as follows:

- *CNC laser cutting*—numerical control cutting of complex shapes.
- *Slip bending rolls*—for the production of tubes from sheet thickness of 0.8 mm to 14 mm and working lengths from 1020 mm up to 4040 mm, hydraulically operated and CNC control.
- *Folding machines*—for sheet thickness from 1.2 mm up to 12 mm and working lengths from 540 mm up to 5040 mm, hydraulically operated and CNC controlled.
- *Press brakes*—for bending pressure of 8000 kN, hydraulically operated with DNC graphical control.
- *Hydraulic swing beam shears and Guillotine shears*—for sheet of between 4 mm and 20 mm and working length 2000 mm to 6000 mm, hydraulically operated with CNC control.
- *Flange press*—for U-forming of rectangular flanges on found, curved, or straight cuts with forced guidance of the sheet.
- *Spot welding*

There are many more types of equipment used in a shipyard, such as portable welding machines, which are discussed in Chapter 20 – Hull Materials and Welding, but the above are the main types.

All the equipment must be laid out in an efficient manner to optimize the material flow. The selection of the equipment and the layout will depend on the planned annual throughput and type and size of ships.

26.5 TYPICAL SHIPYARD CHARACTERISTICS

Table 26.XIII gives the characteristics of a number of shipyards around the world, including the US.

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