The physics of tidal energy

The existence of tides is due primarily to gravitational interaction between the Earth and the Moon. This gravitational force, combined with the rotation of the Earth, produces, at any particular point on the globe, a twice-daily rise and fall in sea level, this being modified in height by the gravitational pull of the Sun and by the topography of land masses and ocean beds. A detailed analysis of this interaction between Earth, Moon and Sun is quite complex, but we will attempt to describe it in simple terms.

The first part of the explanation is relatively straightforward. Starting first with just the Earth and the Moon, the gravitational pull of the Moon draws the seas on the side of the Earth *nearest* to the Moon into a bulge *towards* the Moon. That gives us one tide per day at any one point, as the planet rotates through the bulge. But what about the second tide each day? This is more difficult to explain. Sometimes it is explained in simple terms by saying that the waters that make up the bulge facing the Moon are drawn from the seas at each side of the Earth, but the water at the far side is 'left behind', at its original level. However that does not really explain the fact that the second tide is roughly the same height as the first. Neither does the fact that the water in the seas *furthest* from the Moon experiences slightly less of the lunar pull, being further away, although it may be part of the explanation.

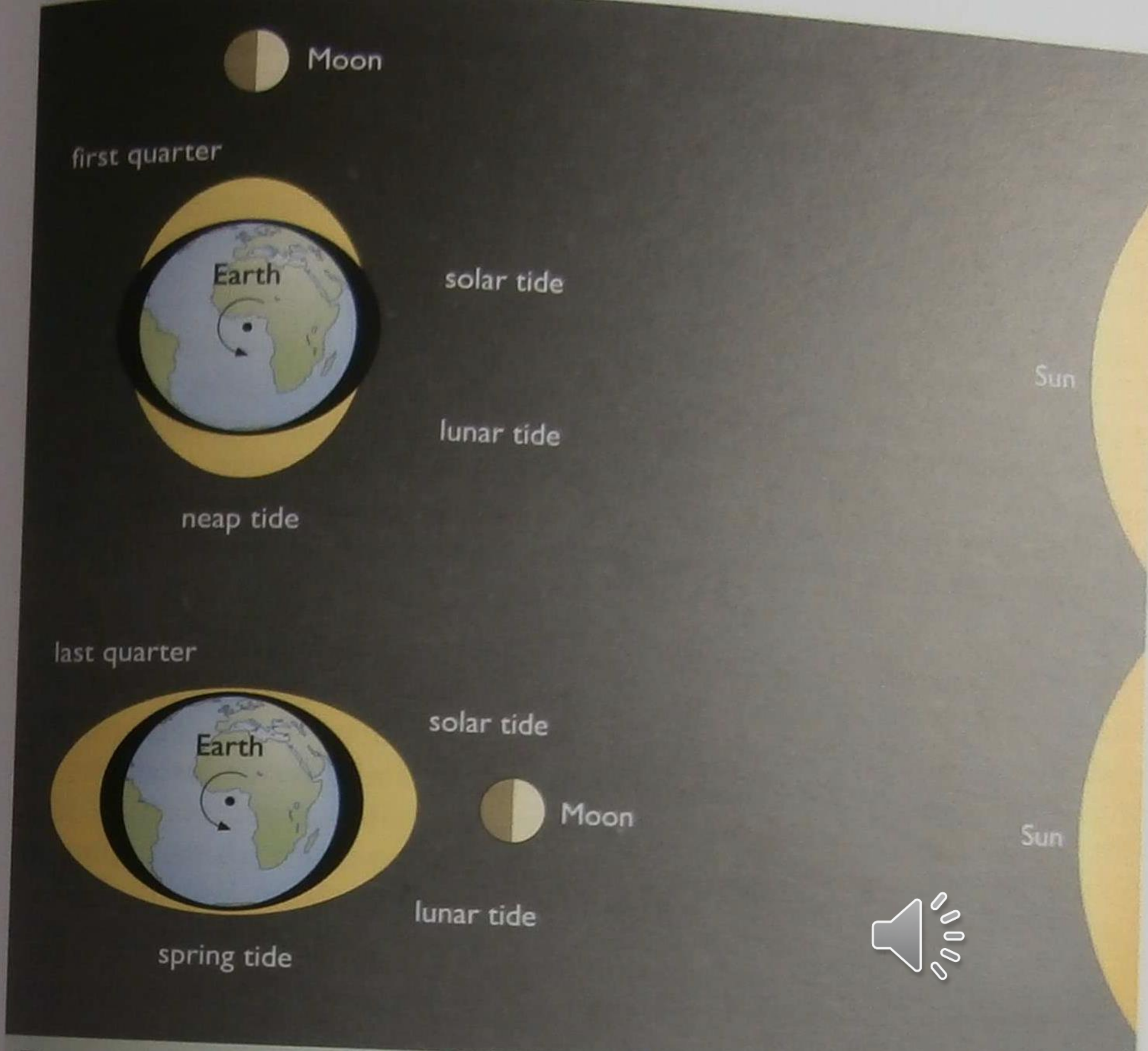


Figure 6.5 Influence of the Sun and the Moon on tidal range (not to scale)

6.2 Power generation from barrages

The basic physics and engineering of tidal barrage power generation are relatively straightforward.

Tidal barrages, built across suitable estuaries, are designed to extract energy from the rise and fall of the tides, using turbines located in water passages

in the barrages. The potential energy, due to the difference in water levels across the barrage, is converted into kinetic energy in the form of fast-moving water which passes through the turbines – the spinning turbines then drive generators to produce electricity.

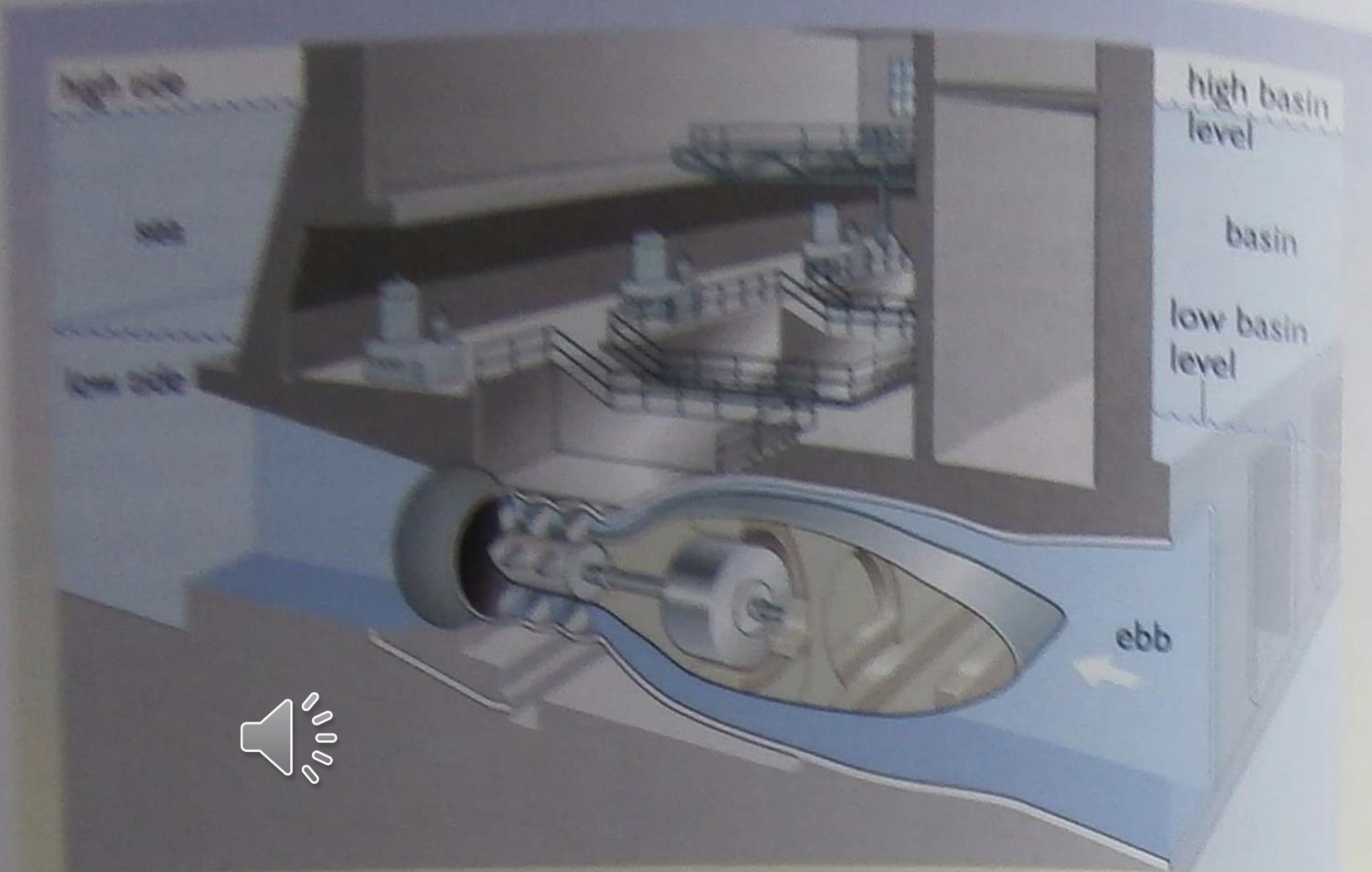


Figure 6.13 Artist's impression of the typical layout of a power generation scheme

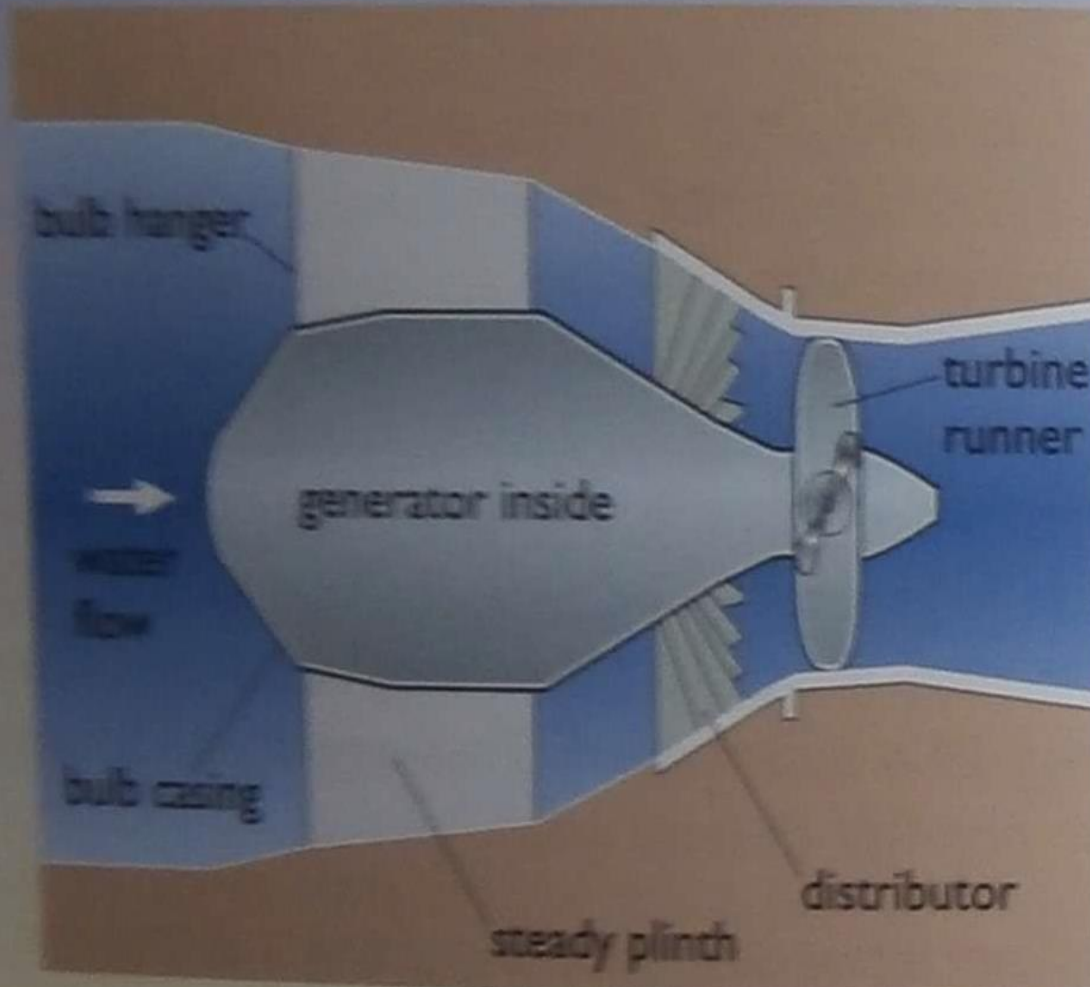


Figure 6.14 Bulb turbine as used at La Rance

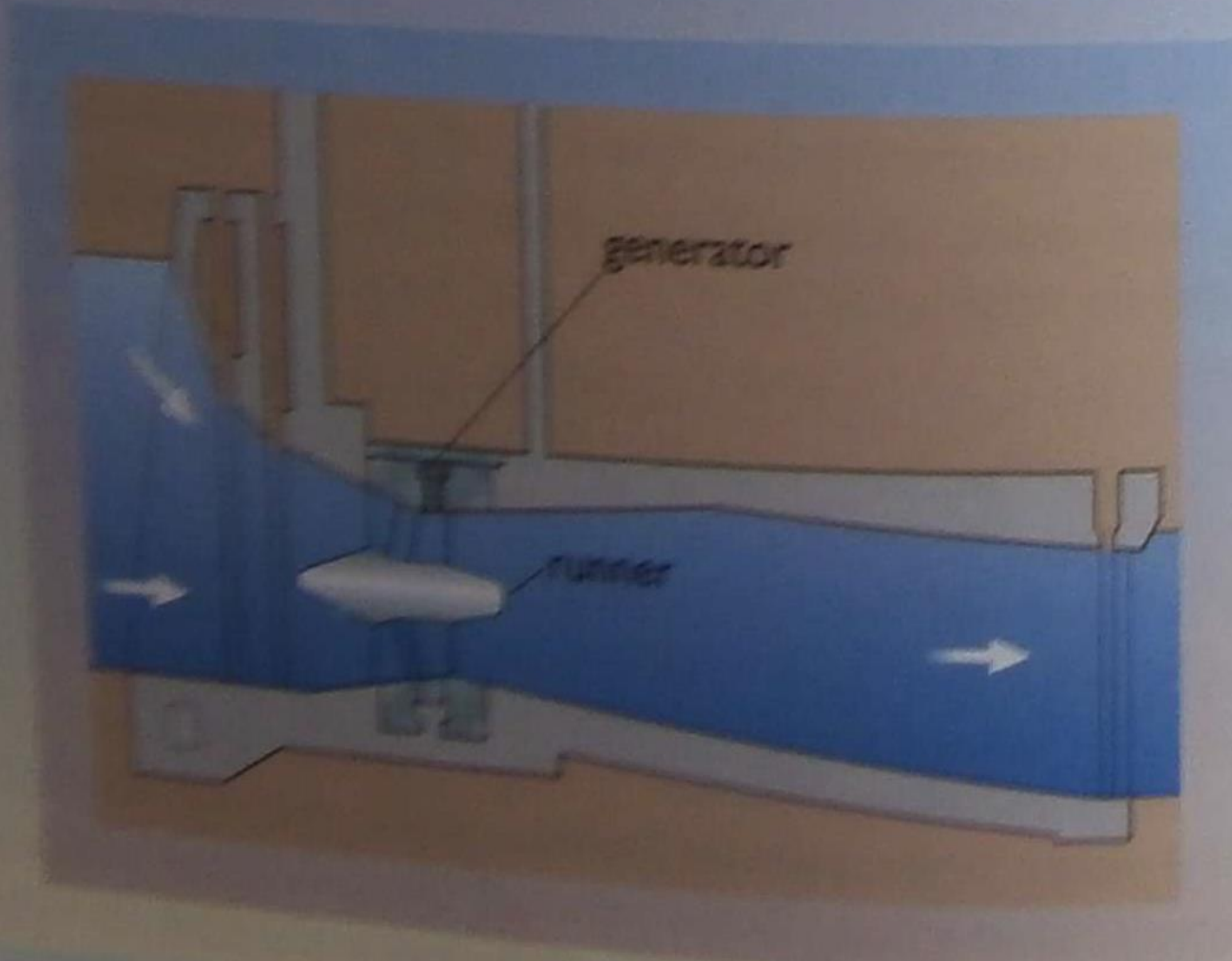


Figure 6.15 Straflo or rim generator turbine as used at Annapolis Royal

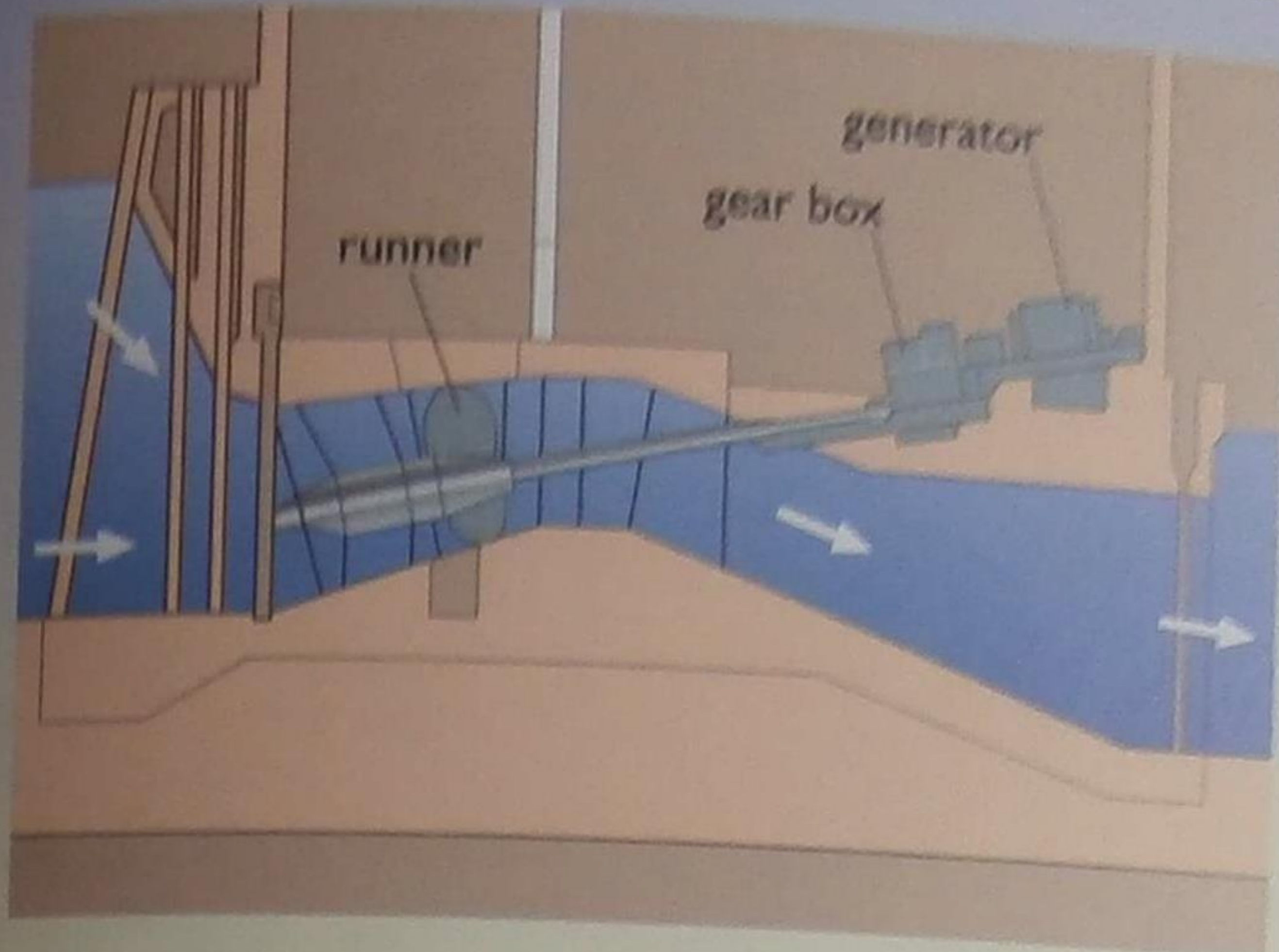


Figure 6.16 Tubular turbine

The 740-metre long Rance Barrage was constructed between 1961 and 1967. It has a road crossing and a ship lock (Figure 6.17) and was designed for maximum operational flexibility. It contains 24 reversible (that is, two-way) turbines, each of 10 MW capacity, operating in a tidal range of up to 12 metres, with a typical head of approximately 5 metres.

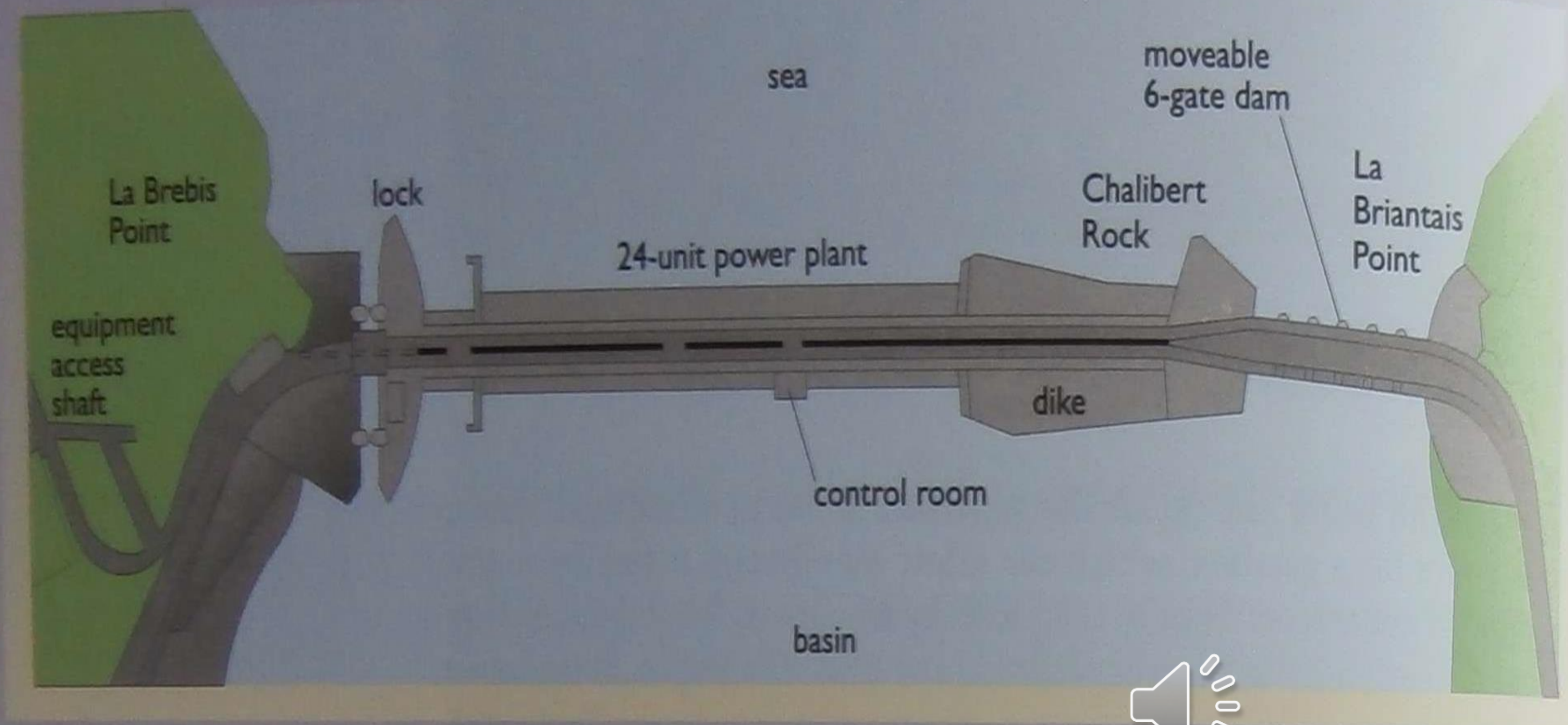


Figure 6.17 Layout of the Rance Barrage (source: Department of Energy, 1981)

Number of turbine generators		216
Diameter of turbines		9.0 metres
Operating speed of turbines		50 rpm
Turbine generator rating		40 MW
Installed capacity		8640 MW
Number of sluices, various sizes		166
Total clear area of sluice passages		35 000 m^2
Average annual energy output		17 TWh
Operational mode		ebb generation with flood pumping
Length of barrage:		
total		15.9 km
including:	powerhouse caissons	4.3 km
	sluice caissons	4.1 km
	other caissons	3.9 km
	embankments	3.6 km
Area of enclosed basin at mean sea level		480 km^2

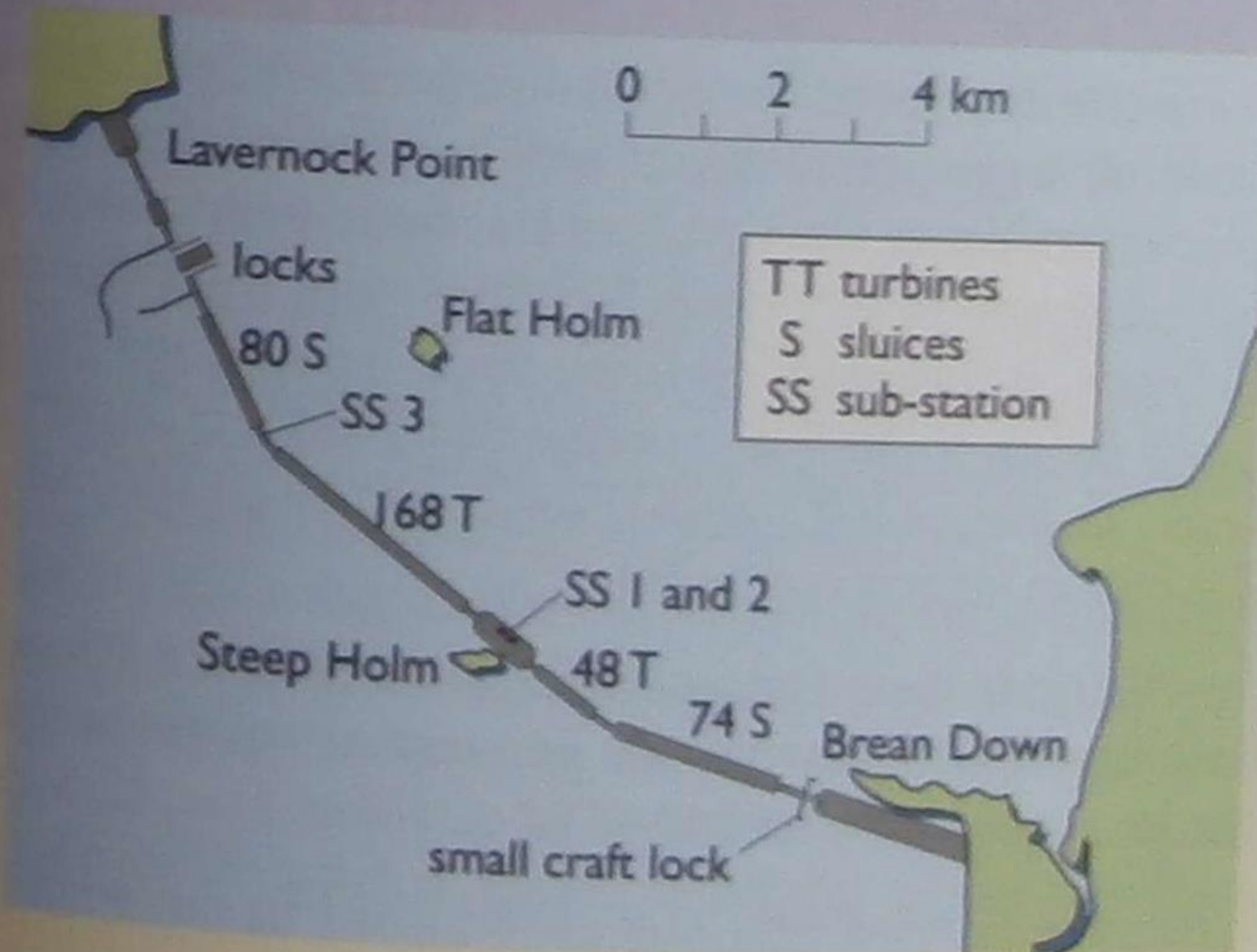


Figure 6.19 Layout of the proposed Cardiff to Weston Severn Barrage (source: adapted from Department of Energy, 1989)

6.4 Integration of electrical power from tidal barrages

The electricity produced by barrages must usually be integrated with the electricity produced by the other power plants that feed into a national grid power transmission network.

The key problem in feeding power from a tidal barrage into national grid networks is that with conventional ebb or flood generation schemes the tidal energy inputs come in relatively short bursts at approximately twelve-hour intervals. Typically, power can be produced for five to six hours during spring tides and three hours during neap tides, within a tidal cycle lasting 12.4 hours (Figure 6.22).

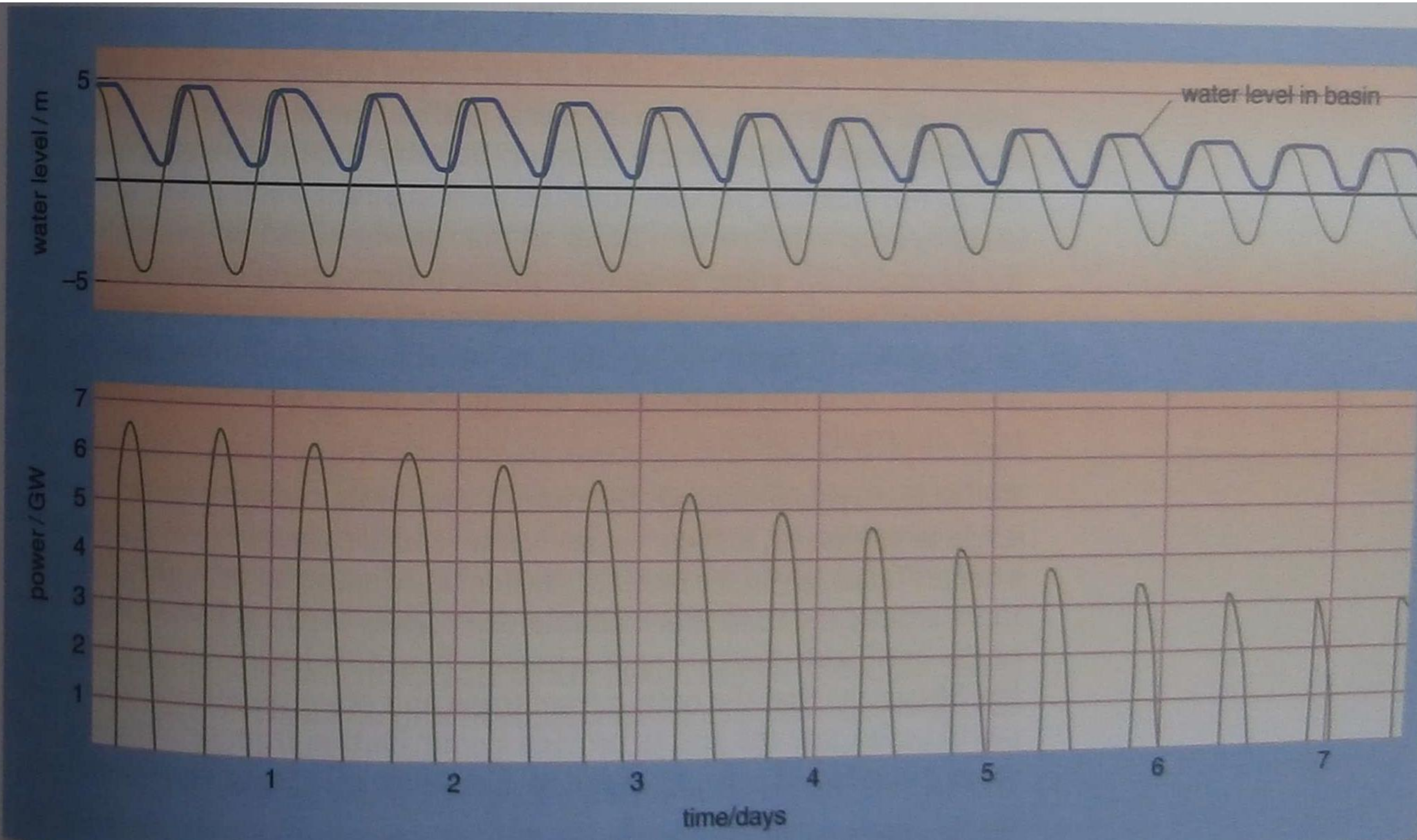


Figure 6.22 Water level and power output of the proposed Severn Barrage over a spring–neap tide cycle (source: Laughton, 1990)

6.7 Tidal lagoons

Somewhat less ambitiously but still speculatively, in addition to large barrages, there have also been proposals for offshore 'bounded reservoir' or 'tidal lagoon' systems, consisting of circular low-head dams in open water, trapping water at high tide, with the water then being released to drive turbines in the usual way (Figure 6.25).

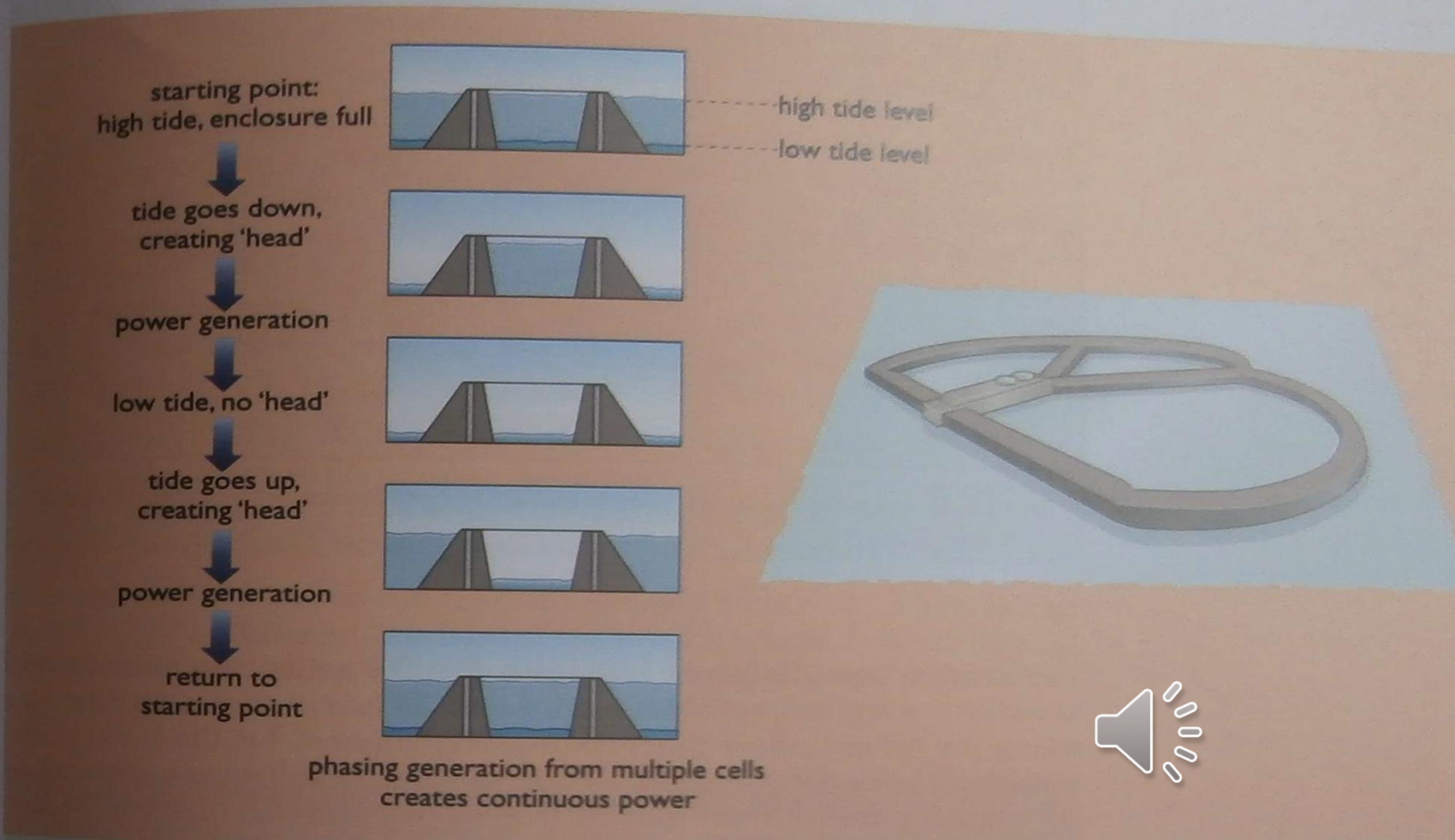


Figure 6.25 Tidal Electric's 'bounded' reservoir proposal

Lagoons would be in relatively shallow water and would be constructed like causeways with rock infill. Lagoons have the key advantage that although, as with conventional barrages, they would involve the creation of a head of water, they would not involve blocking off an estuary and so should have a lower environmental impact and avoid interfering with the passage of ships.

As well as generating power directly for the grid, lagoons might also be used as a low-head offshore pumped storage facility (see Chapter 5). Moreover, as with the double barrage idea, segmented lagoons could enable phased operation and pumping between segments.

Tidal current turbine design constraints

When considering device design and location it is crucial to note that friction with the seabed produces a vertical 'shear' effect in the current: surface water moves fastest, with the flow being slower lower down. Around 75% of the energy in the flow is contained in the top half of the water (Figure 6.29), but since the rotors have to be fully submerged, and to be efficient and avoid breaking the surface, a mid-depth location can make sense, with the size of the device being limited by the water depth. Given that most sites with high velocity water flow are relatively shallow (below 40–50 metres), tidal devices thus have a size constraint that does not apply to wind turbines.

Since the available energy is proportional to the square of the rotor blade length and the cube of the water velocity, even a small increase in blade size or water speed will yield a significantly increased amount of energy production. Figure 6.30 shows how the relationship works out in practice – the faster the flow and the larger rotor (subject to practical considerations) the better.

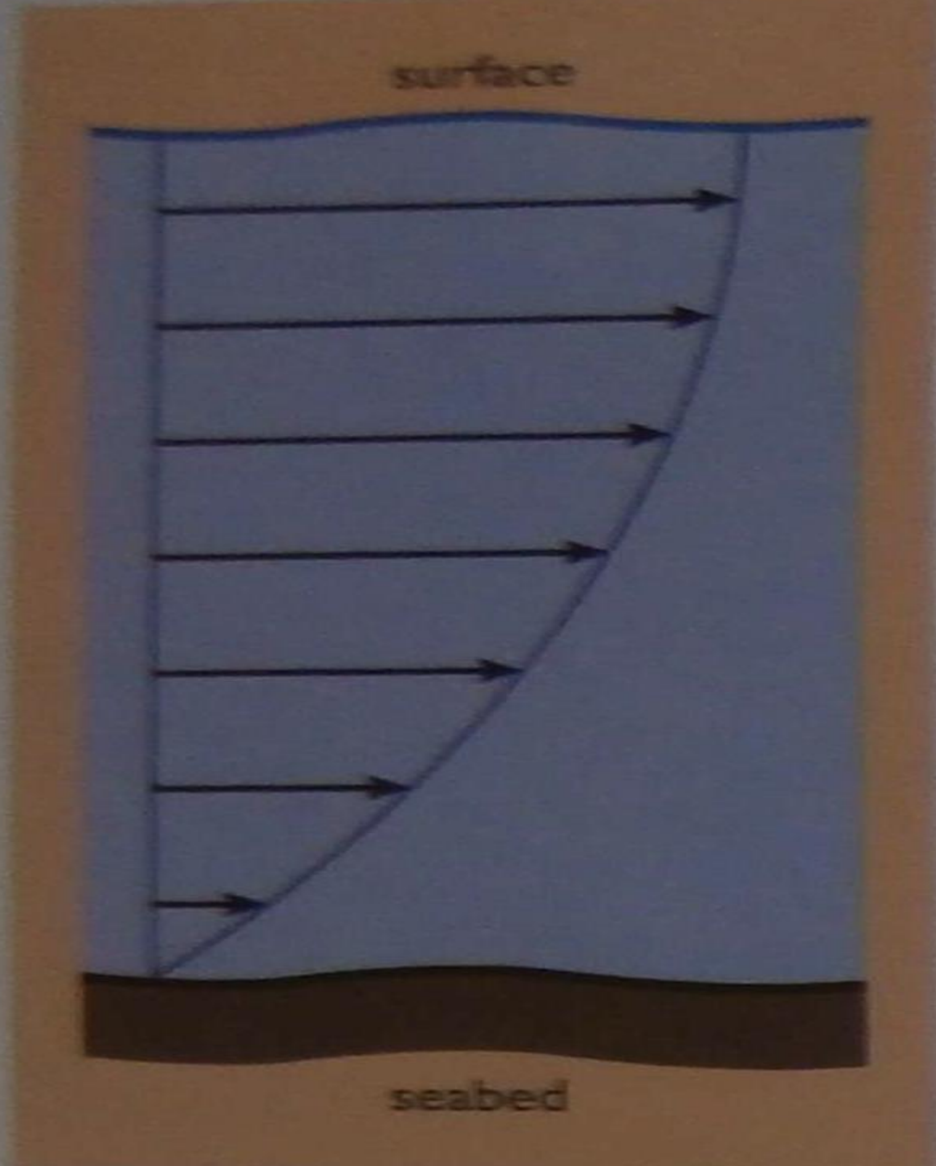


Figure 6.29 The shear effect – water speed (as indicated by arrow length) reduces with depth

Since the available energy is proportional to the square of the rotor blade length and the cube of the water velocity, even a small increase in blade size or water speed will yield a significantly increased amount of energy production. Figure 6.30 shows how the relationship works out in practice – the faster the flow and the larger rotor (subject to practical considerations) the better.

Submerged free-standing tidal rotors can operate at lower rotational speeds than wind turbines, the rotor speed in both cases being proportional to the flow velocity, with typical sea current velocities only being approximately 3 m s^{-1} compared with, say, 5–15 m s^{-1} for wind machines. Given that the density of the working fluid is much higher, the power output for a tidal stream machine is much larger than for a wind machine of equivalent rotor diameter.

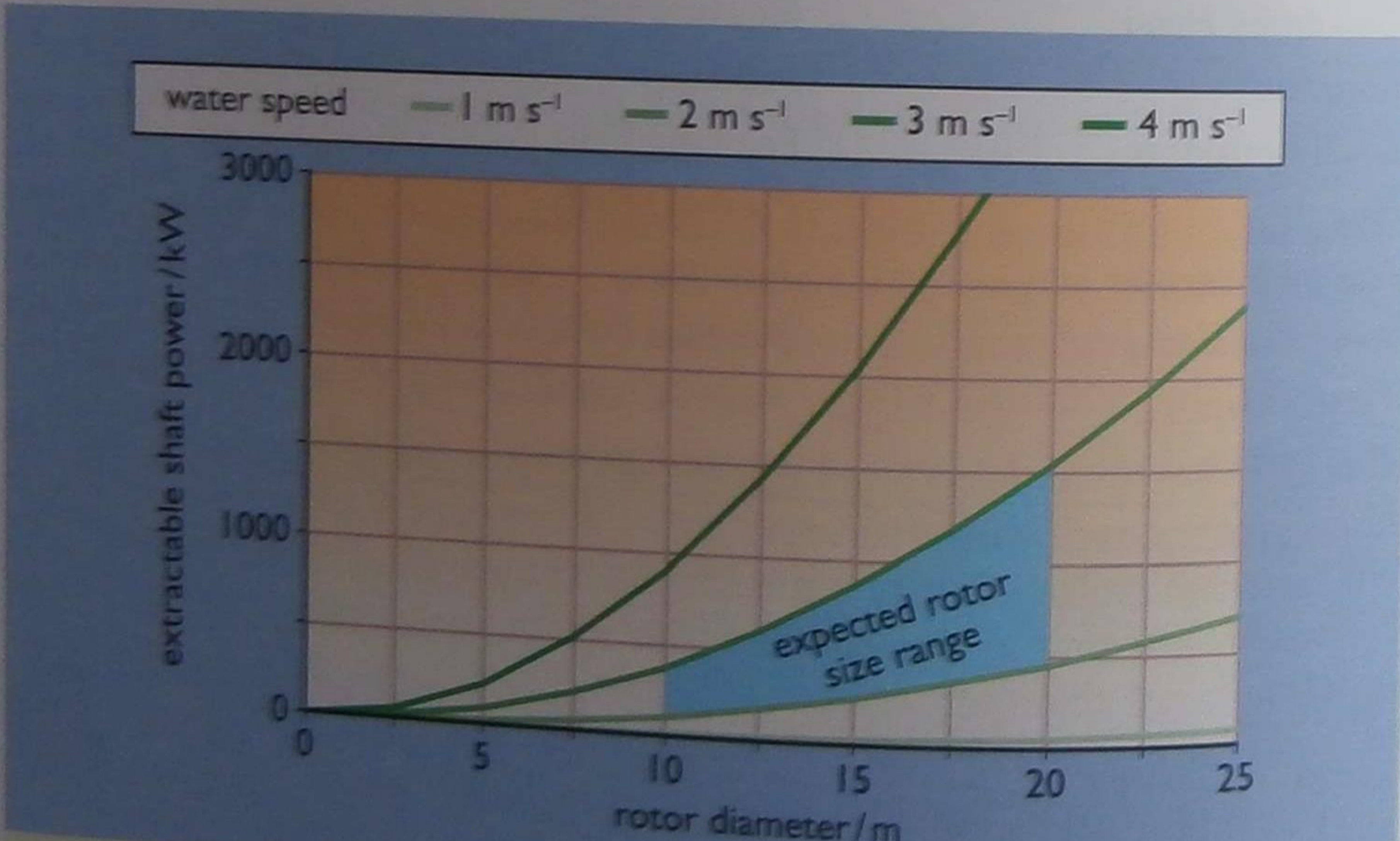


Figure 6.30 Relationship between rotor diameter, water speed and extractable power (source: adapted from Marine Current Turbines, 2010)

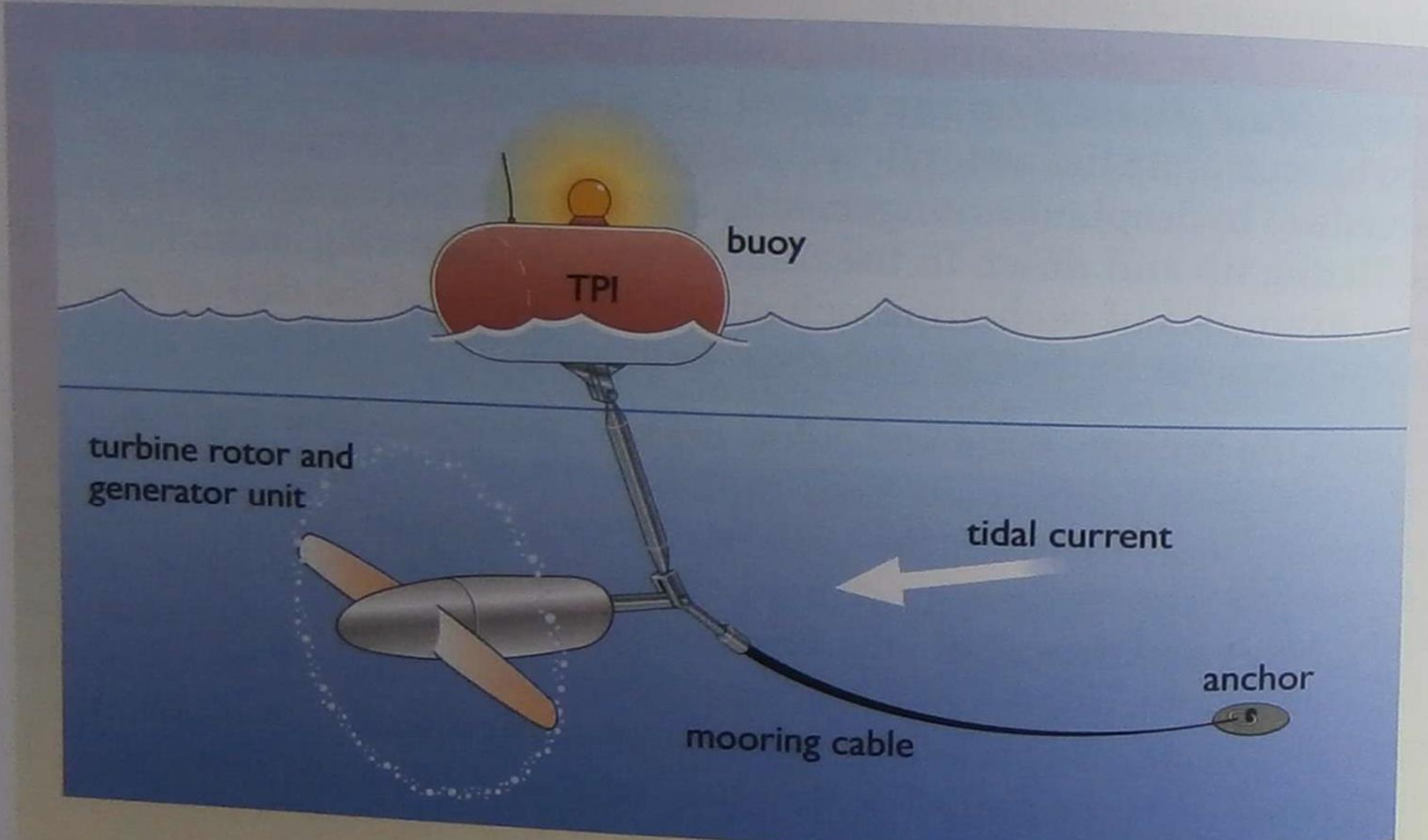


Figure 6.31 The IT Power tidal current turbine concept, developed and tested at Loch Linnhe, Scotland (source: adapted from Marine Current Turbines, 2010)

This free-floati

Figure 6.32 MCT 1.2 MW SeaGen in Strangford Narrows with the rotor blades raised out of the water for access

Novel designs

The turbines we have looked at so far may look like aircraft or ship propellers, but of course they do not propel anything – they absorb energy from the tidal flow. Propeller-type configurations have certainly been popular, but they are not the only option and the tidal turbine field is currently at the innovative stage where many different concepts are being proposed and tested. For example the Engineering Business group developed a novel design - the **Stingray** - with a set of totally submerged hydroplanes, oscillating up and down in the tidal flows and driving a generator mounted on the seabed

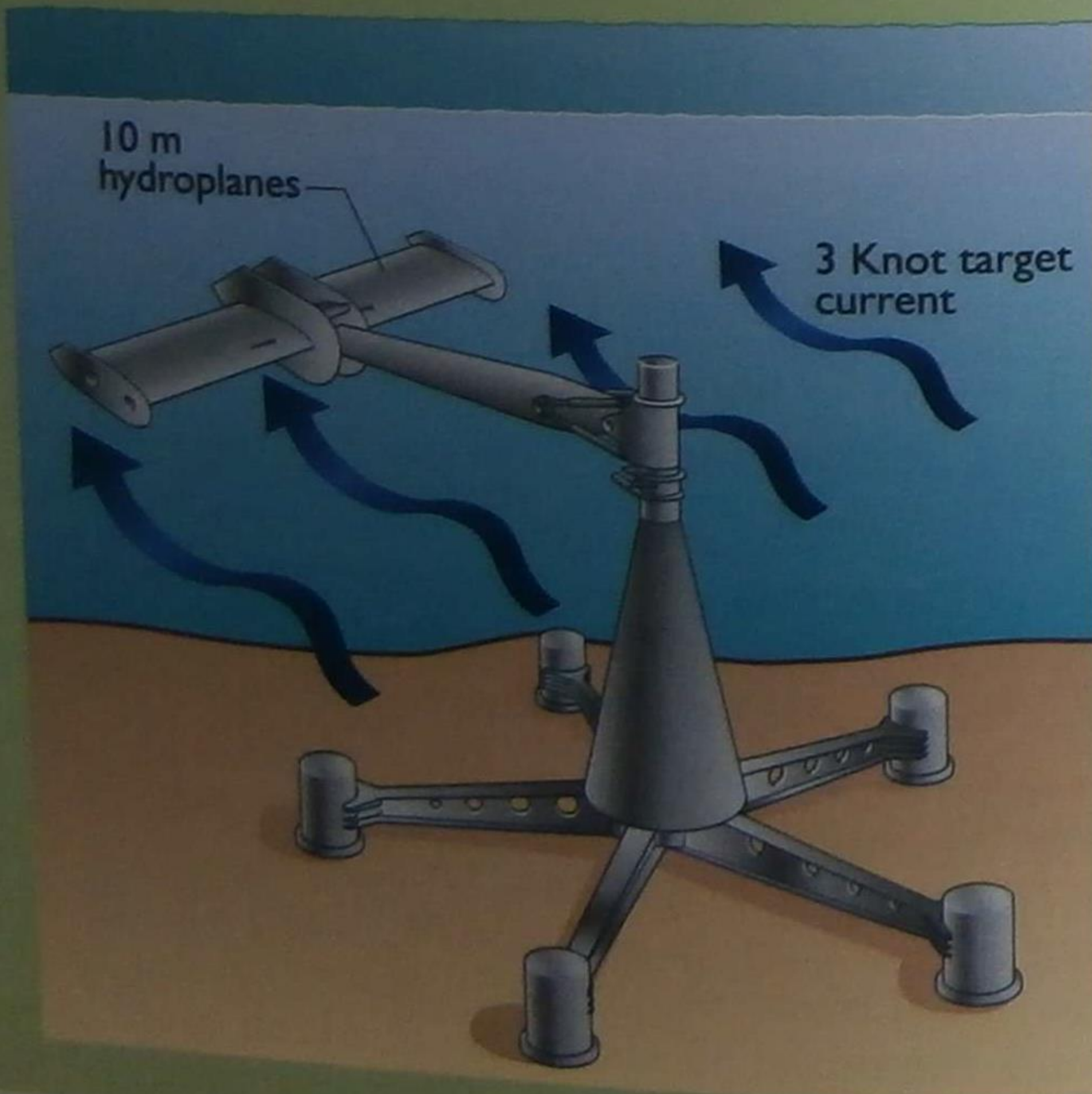


Figure 6.33 Stingray tidal generator

Figure 6.34 Pulse Tidal's two hydrofoils mounted on a see-saw concept

Figure 6.35 Example of a ducted rotor being developed by Rotech

Figure 6. 36 Neptune's Proteus – a vertical-axis ducted rotor

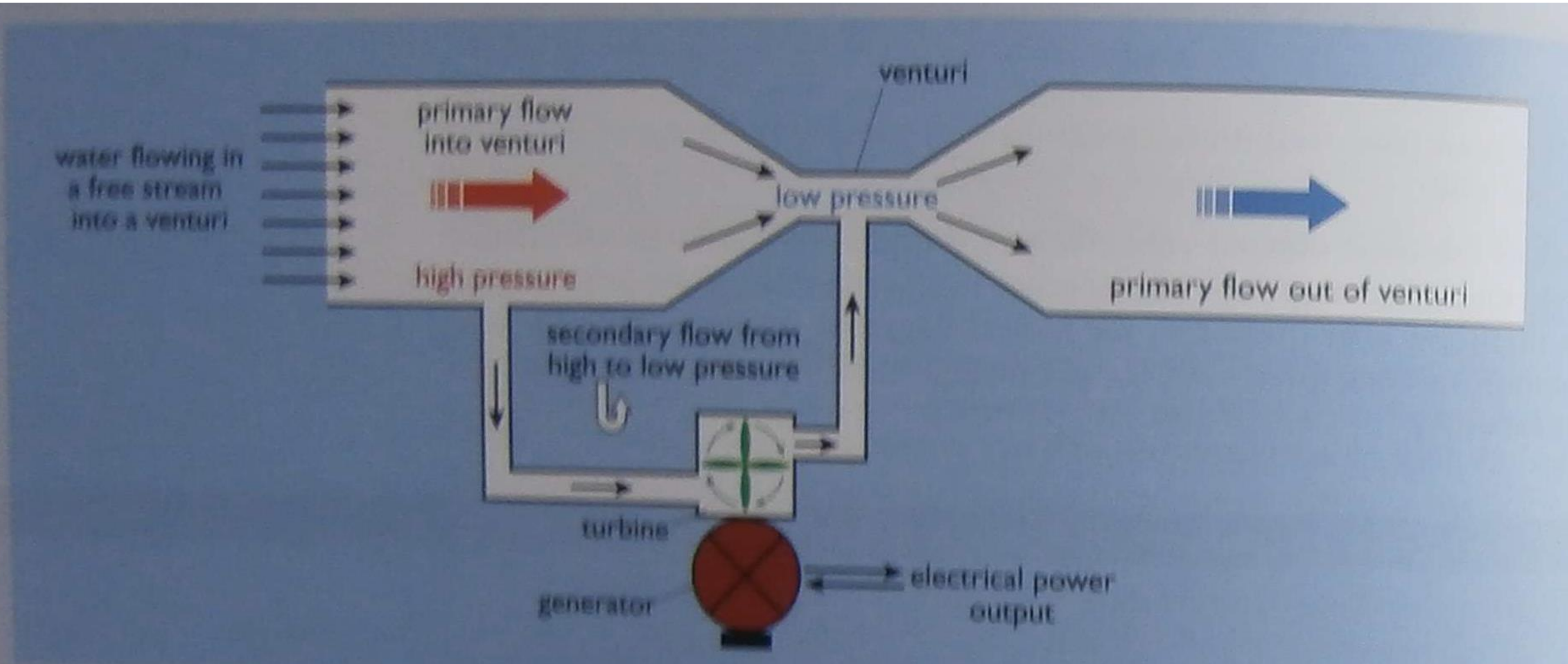


Figure 6.41 SMEC 'venturi' concept – basic principles (source: adapted from VerdErg, 2009)

Spectral Marine Energy Converter (SMEC)

A third project looked at under SETS was the Spectral Marine Energy Converter (SMEC), a novel device being developed by VerdErg using the venturi effect – the reduction in fluid pressure that results when a fluid flows out through a constriction. In this system the tidal flow passes through vanes, creating a pressure drop which is used to drive a turbine and generator via a secondary water flow. The secondary flow will have a higher velocity than the primary flow (Figure 6.41). Furthermore this secondary flow can power a turbine and generator located more conveniently out of the water.

The SMEC concept could be used at a variety of scales – in free-standing mid-stream locations in rivers, or across whole estuaries in a permeable fence-like structure. Vertical vanes would be used in the latter case to produce the pressure drop, horizontal vanes for shallow mid-channel use in rivers (see Figure 6.42). An estuary-wide tidal fence version (Figure 6.43), would, VerdErg claims, produce nearly as much electrical power as a full conventional barrage, but at two thirds of the cost and with much less environmental impact.

Reporting on the outcome of the SETS project in 2010, DECC's Severn Tidal Feasibility Study noted that the tidal bar/reef and the Spectral Marine Energy Converter 'showed promise for future deployment within the Severn estuary – with potentially lower costs and environmental impacts than either lagoons or barrages.' However they added 'these proposals are a long way from technical maturity and have much higher risks than the more conventional schemes the study has considered. Much more work would be required to develop them to the point where they could be properly assessed.' (DECC, 2010a).

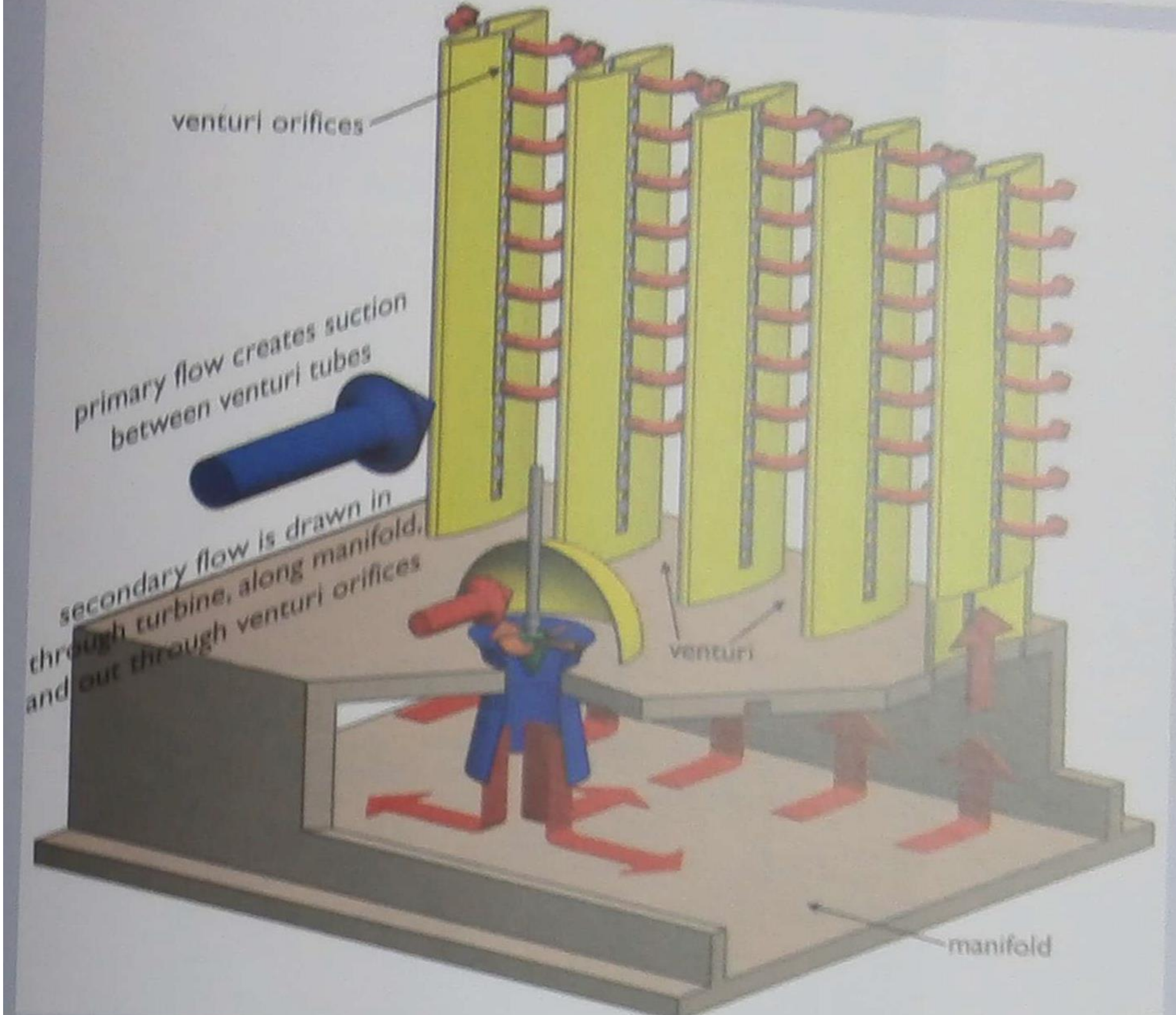


Figure 6.42 Proposed SMEC tidal system for a river

Figure 6.43 Proposed SMEC tidal fence system for an estuary.

Figure 6.44 The Hammerfest Strøm tidal turbine

Figure 6.45 Atlantis AK-1000 1MW double rotor tidal turbine

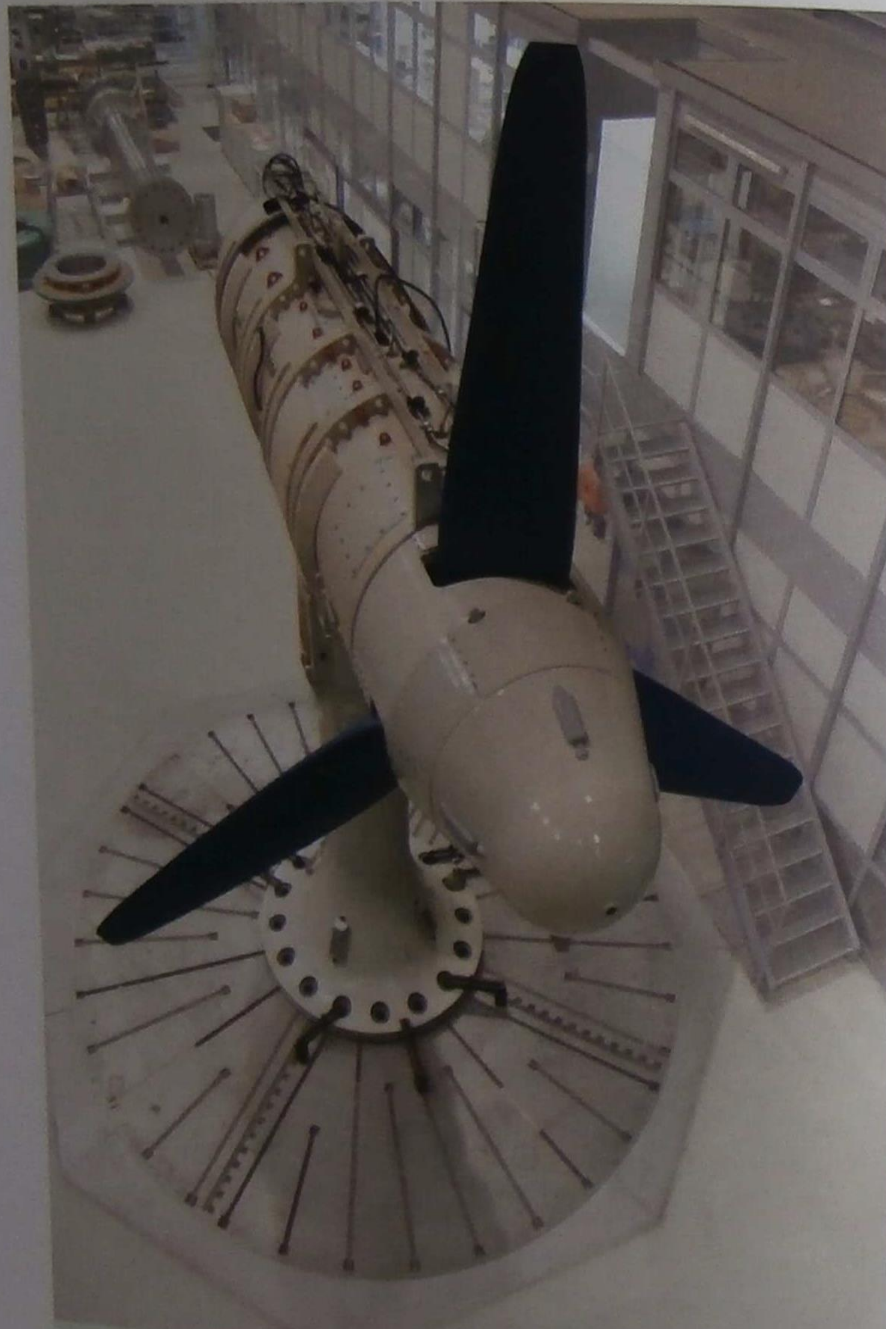


Figure 6.46 Voith 1 MW turbine

Tidal current systems may also be easier to develop than the wave energy systems described in Chapter 8. Whereas wave energy systems have to operate in a chaotic interface between air and water and have to try to capture energy from multiply-vectored wave motions using complex technology, tidal currents are smoother, laminar flows, in a much more stable, although still turbulent, undersea environment, and the energy can be captured using relatively simple turbines.

8.5 Wave energy technology

In order to capture energy from sea waves it is necessary to intercept the waves with a structure that will react in an appropriate manner to the forces applied to it by the waves. In the case of a shore-mounted device, like TAPCHAN and most OWC devices, the structure is firmly fixed to the seabed, and the waves make water move in a useful way. For other types of device some part of the structure may be fixed, perhaps anchored to the seabed, but another part may be a float which moves in response to the waves by pulling against the anchor. In this case the relative motion between the anchor and the float provides the opportunity to extract energy.

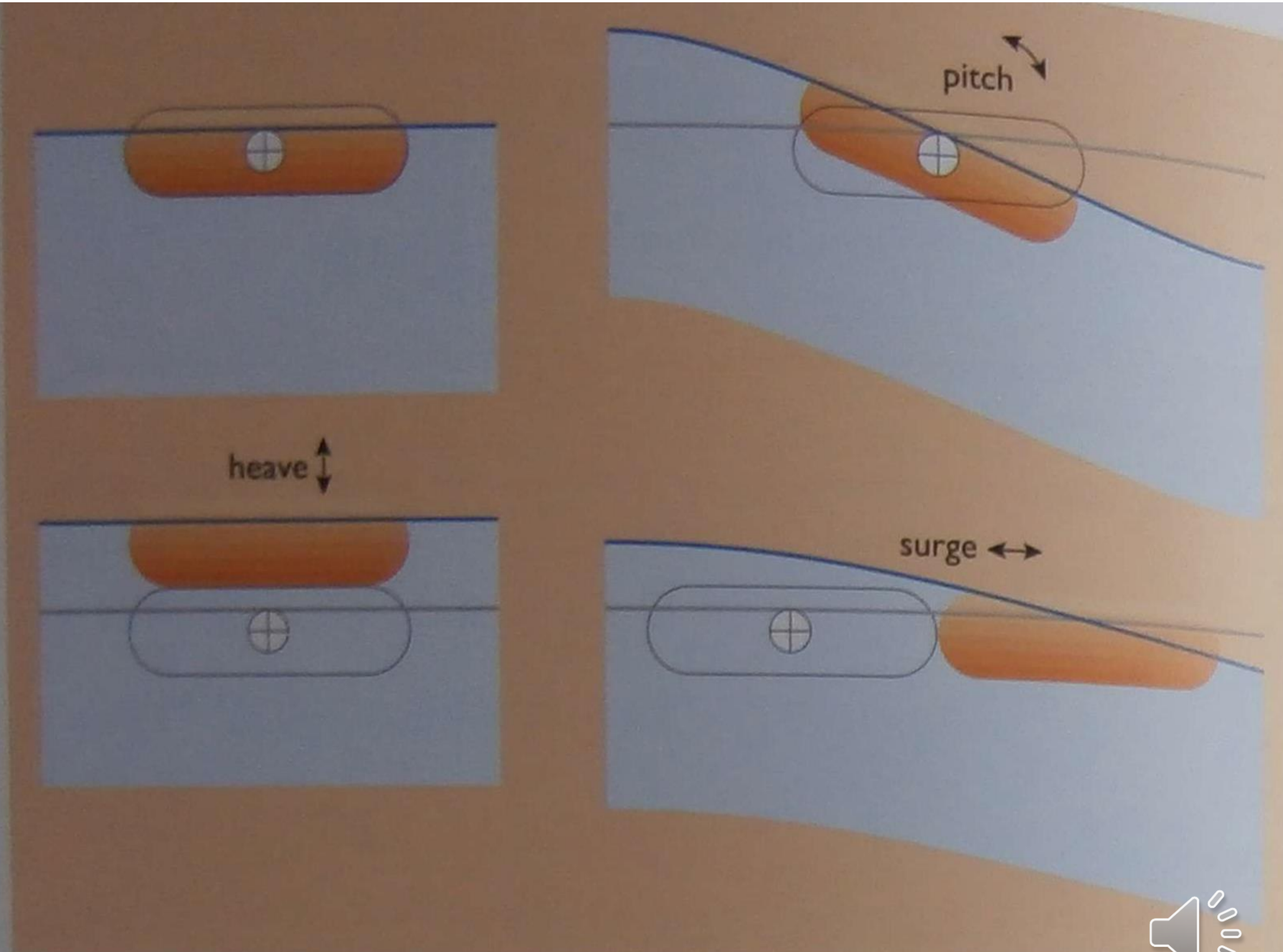


Figure 8.14 The pitch, heave and surge responses of a floating object to incident waves

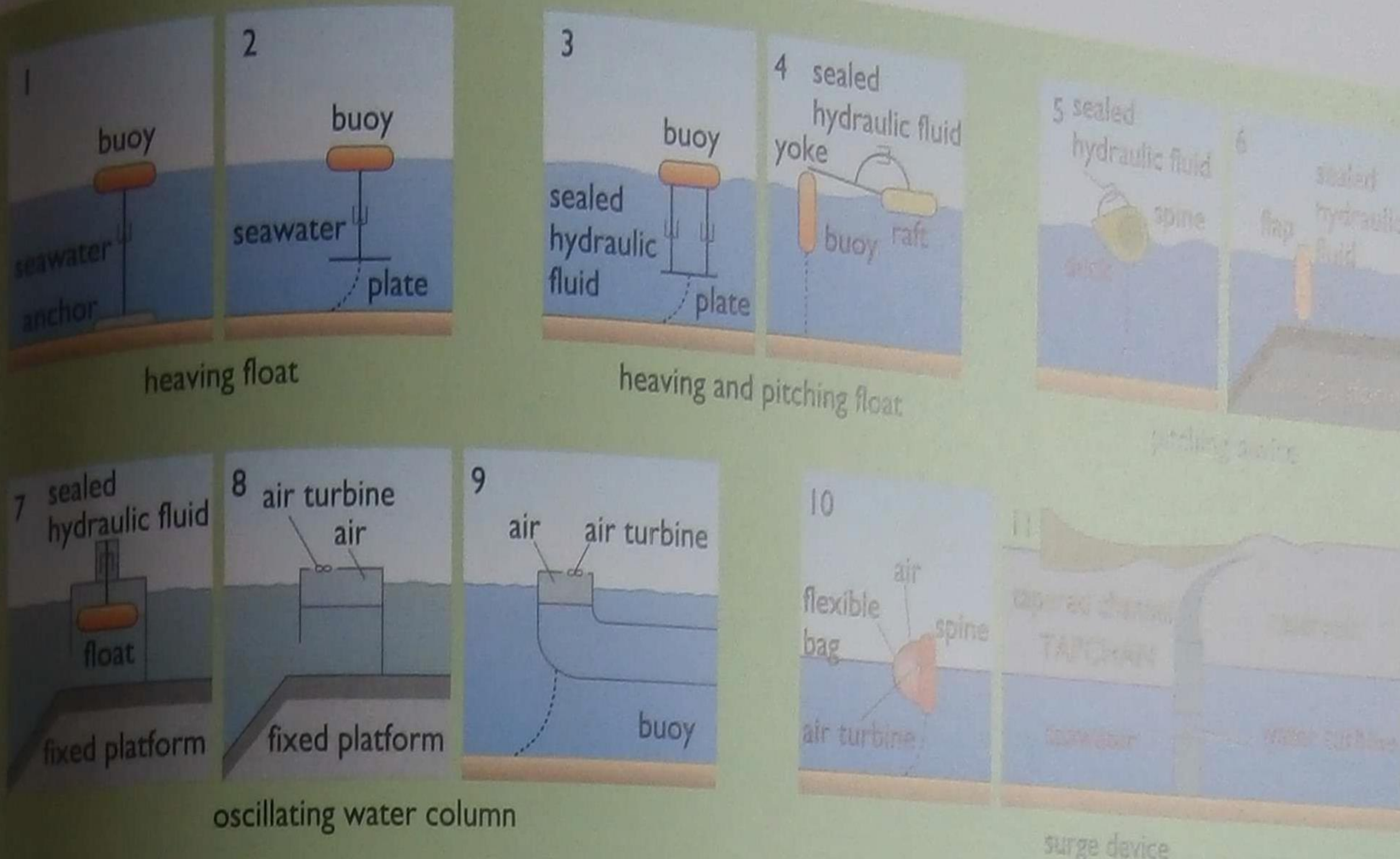


Figure 8.15 Schematic representation of various types of wave energy converter (source: based on Falnes and Lovseth, 1991)

Another approach is to consider the device location (Figure 8.16) – here the three general classifications are:

- fixed to the seabed, generally in shallow water (eg TAPCHAN)
- tethered in intermediate depths (eg Oyster)
- floating offshore in deep water (eg AWS-III).

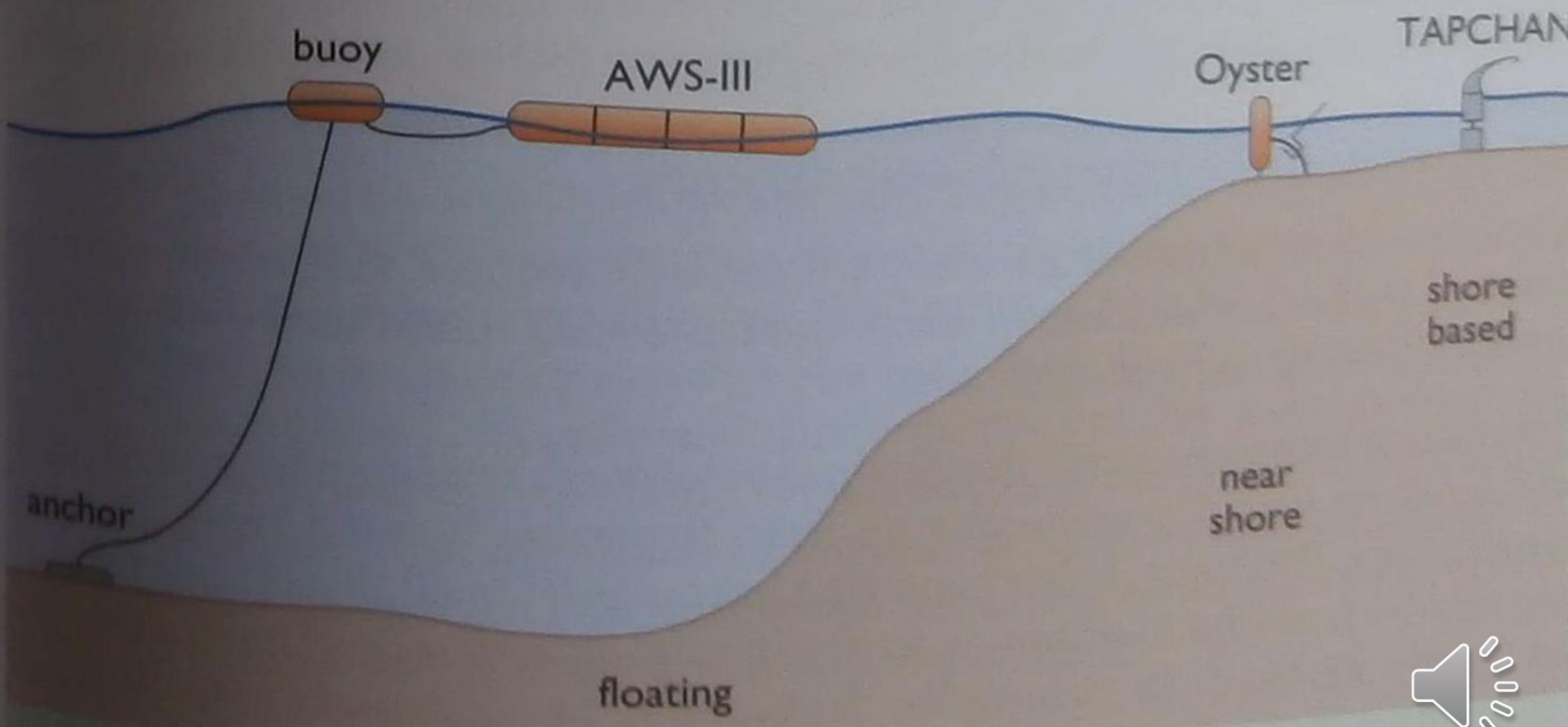


Figure 8.16 Classification of wave energy converters according to location

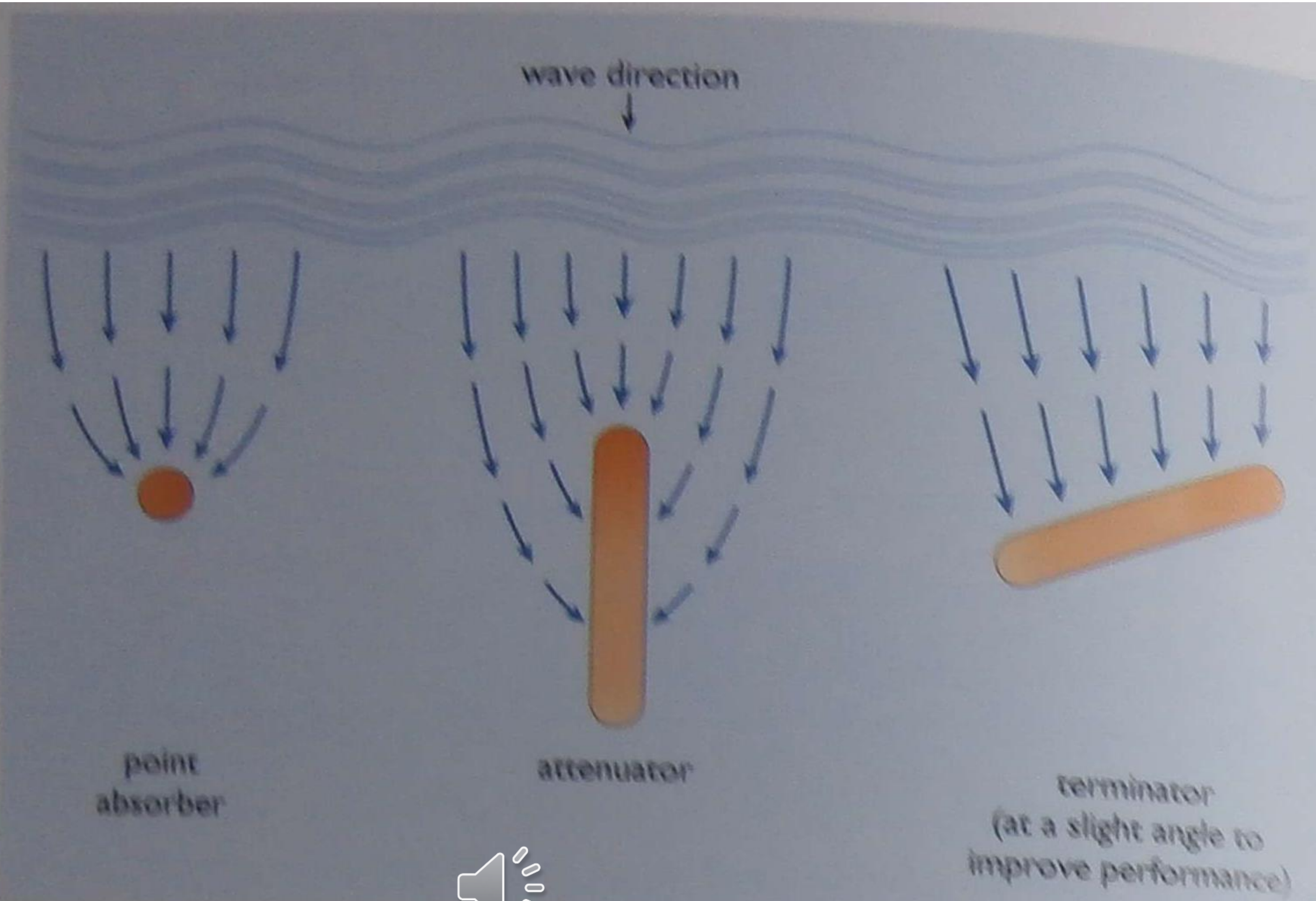


Figure 8.17 Classification of wave energy converters according to size and orientation

Terminator devices have their principal axis parallel (or almost parallel, since a slight angle helps to increase the stability of the whole body) to the incident wave front, and they physically intercept the waves. Depending on the depth, a 300 m long device in a wave climate of 60 kW per metre thus intercepts up to 300 × 60 kW = 18 000 kW. Typically 1/3 of this might be converted into electricity (i.e. 6 000 kW). The terminator might be moored to a leading buoy and anchor, which allows the terminator to pivot as the wave direction changes.

Attenuators have their principal axis perpendicular to the wave front, so that wave energy is gradually drawn in towards the device as the waves move along it. A leading buoy and anchor permit the device to swing round and orientate to the principal wave direction.

An array of terminators or attenuators will require sufficient spacing between individual devices to allow them to swing round on their moorings without fouling their neighbours.

Point absorbers have small dimensions relative to the incident wavelength and work by drawing wave energy from the water beyond their physical dimensions. Typically, being sensitive to waves from all directions, they do not require freedom to orientate to the incoming waves, and so can usually be tightly moored. In principle, they could be extremely slim vertical cylinders which execute large vertical excursions in response to incident waves, but in practice the hardware involved tends to mean that they are a few metres in diameter and absorb energy from perhaps twice their own width. Tethered buoy systems, for example, act as point absorbers.

Point absorber theory

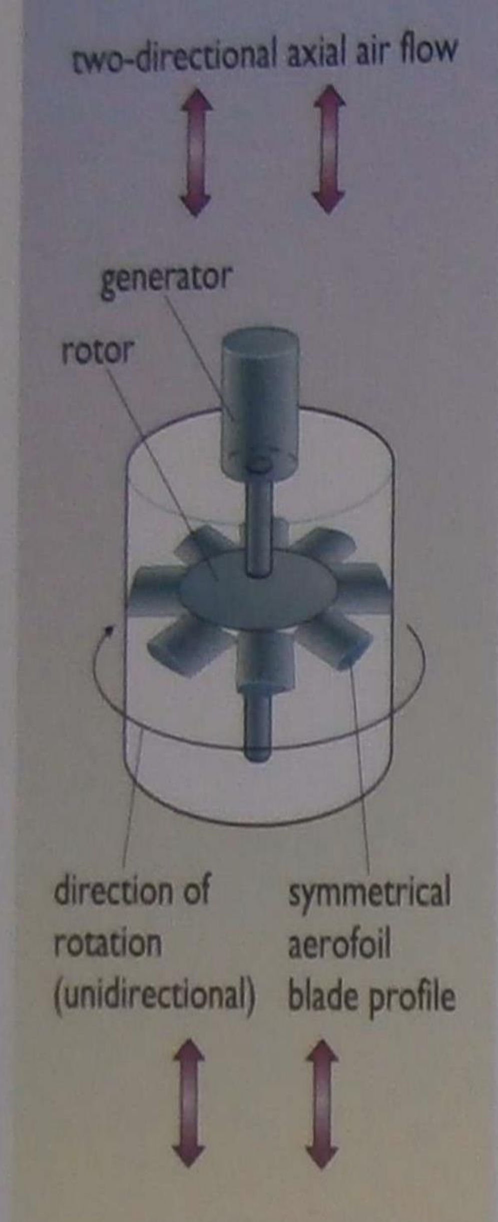
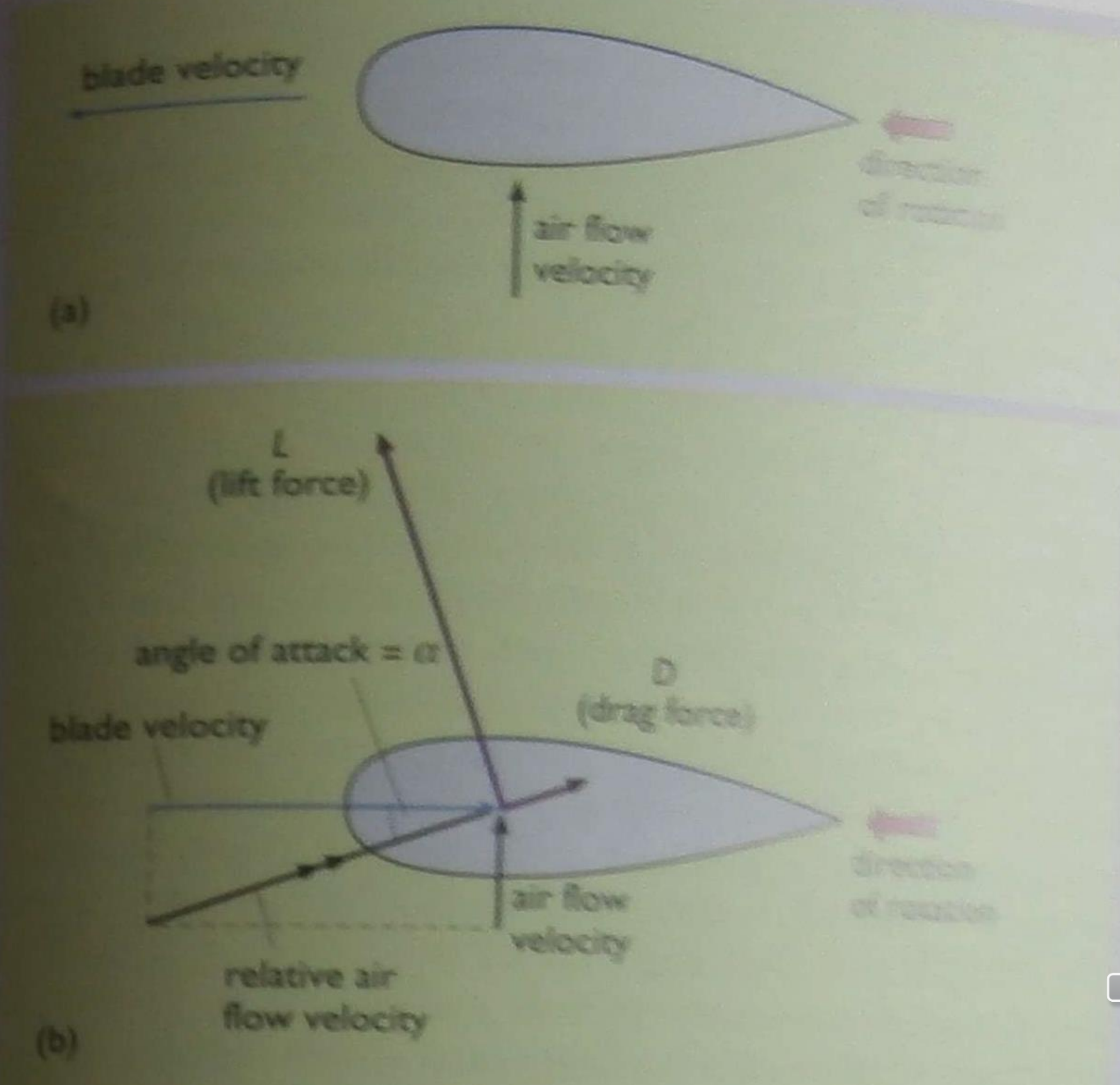


Figure 8.19 The Wells turbine


blade velocity
air flow velocity
(a)
L
(lift force)
angle of attack = α
D
(drag force)
blade velocity
air flow velocity
relative air flow velocity
(b)

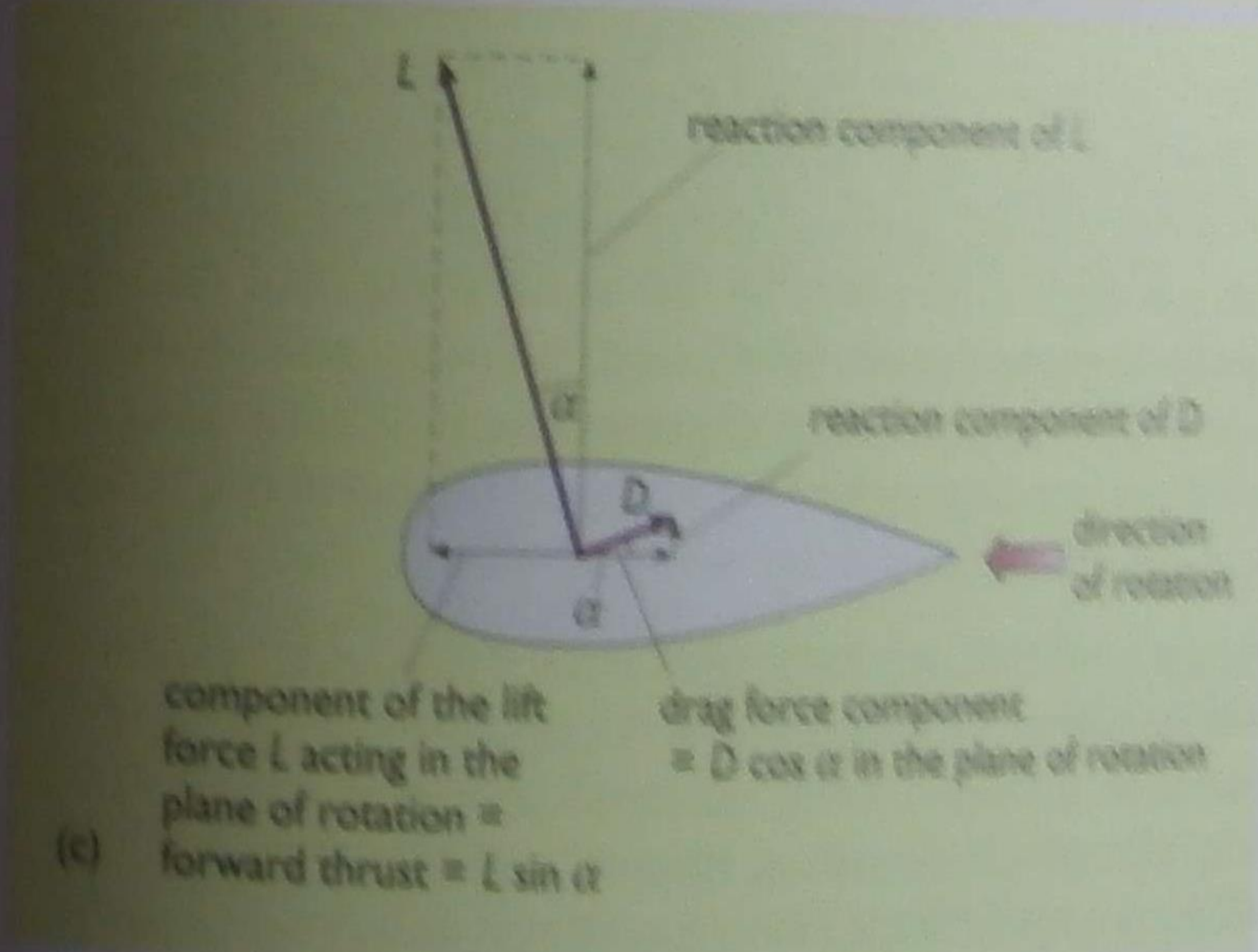


Figure 8.20 The Wells turbine (a) airflow and blade velocity; (b) relative air velocity and lift and drag forces; (c) forces in the plane of rotation

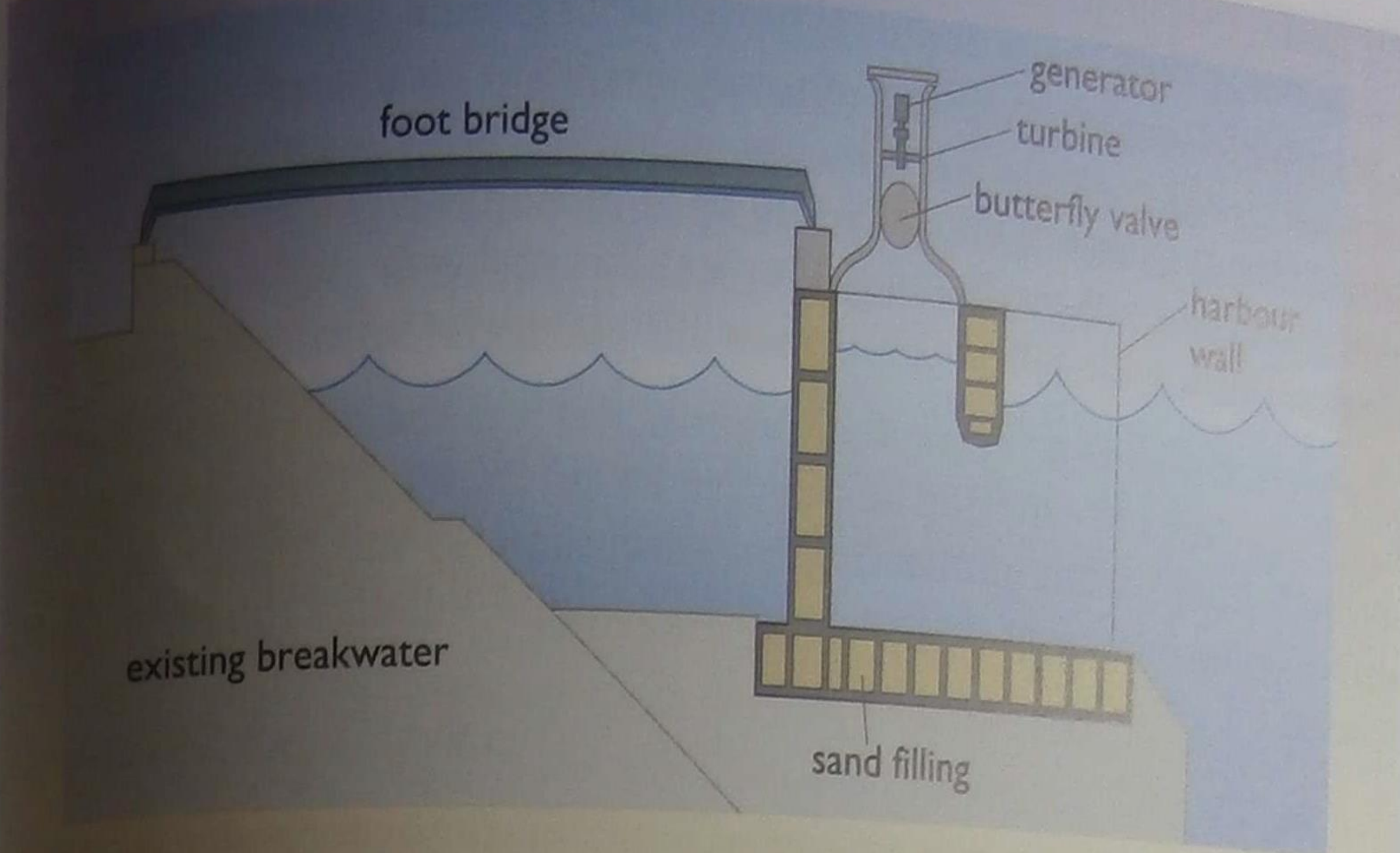


Figure 8.21 Cross-section through the Indian breakwater OWC

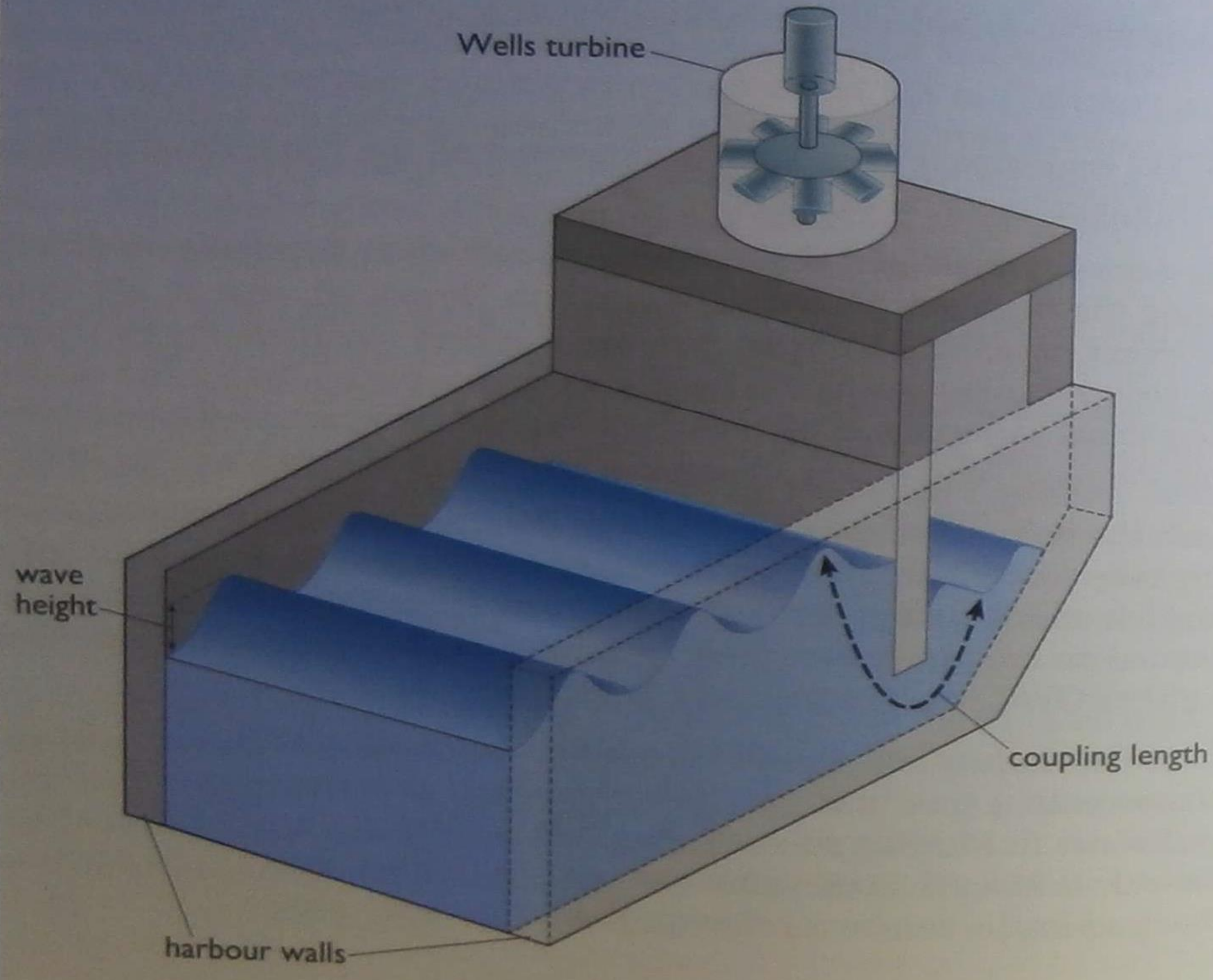


Figure 8.22 A multi-resonant oscillating water column

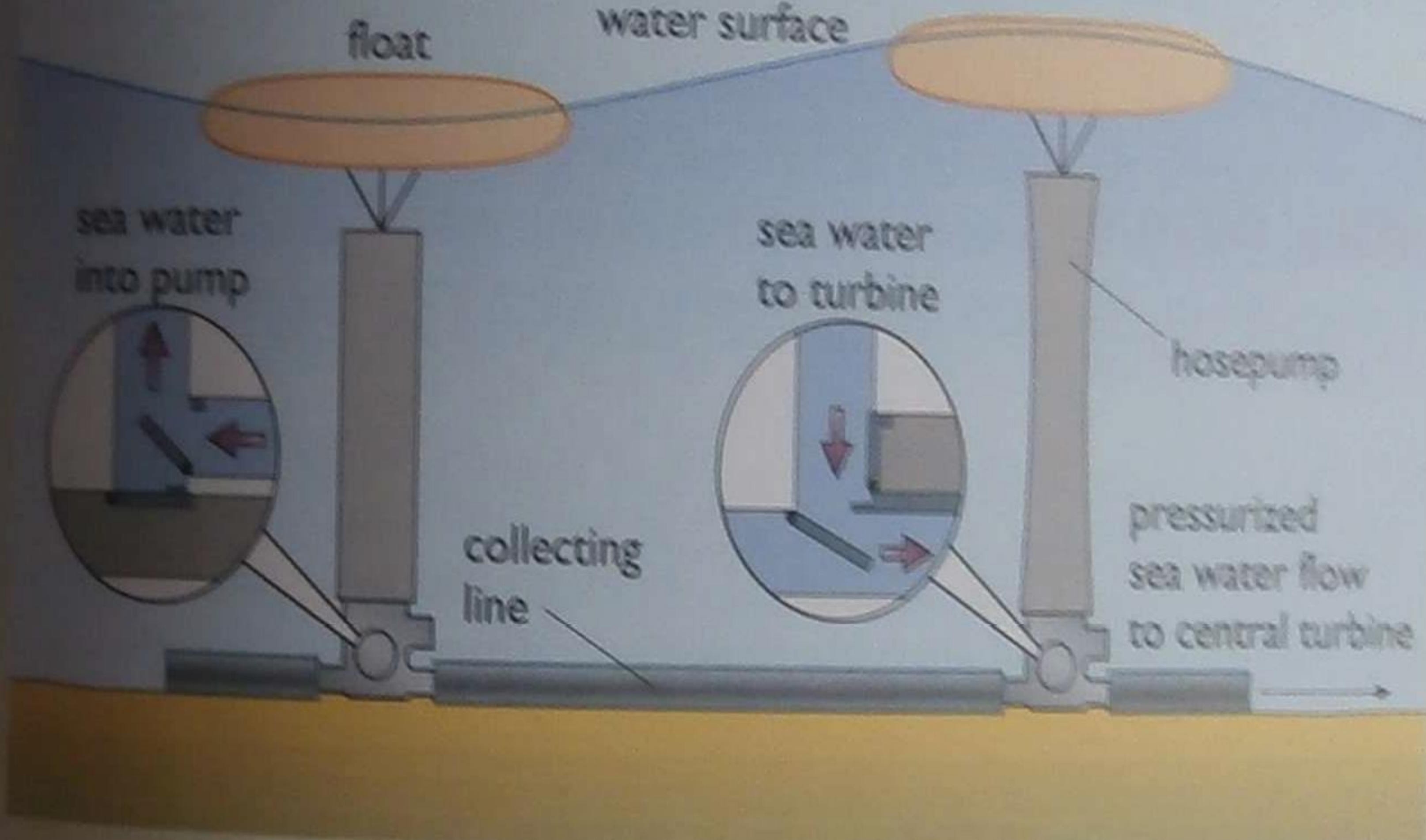


Figure 8.25 Swedish hose pump wave energy converter

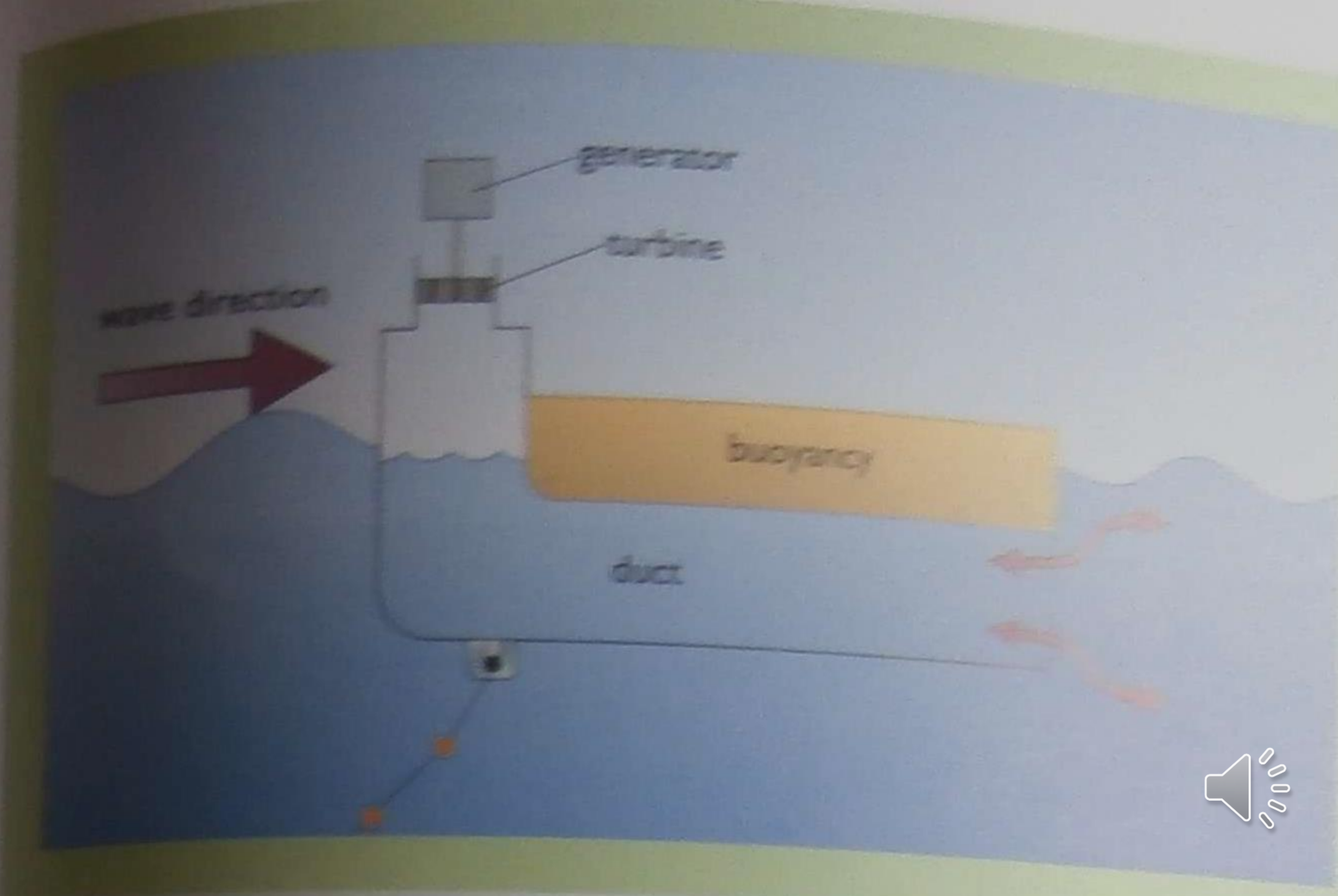
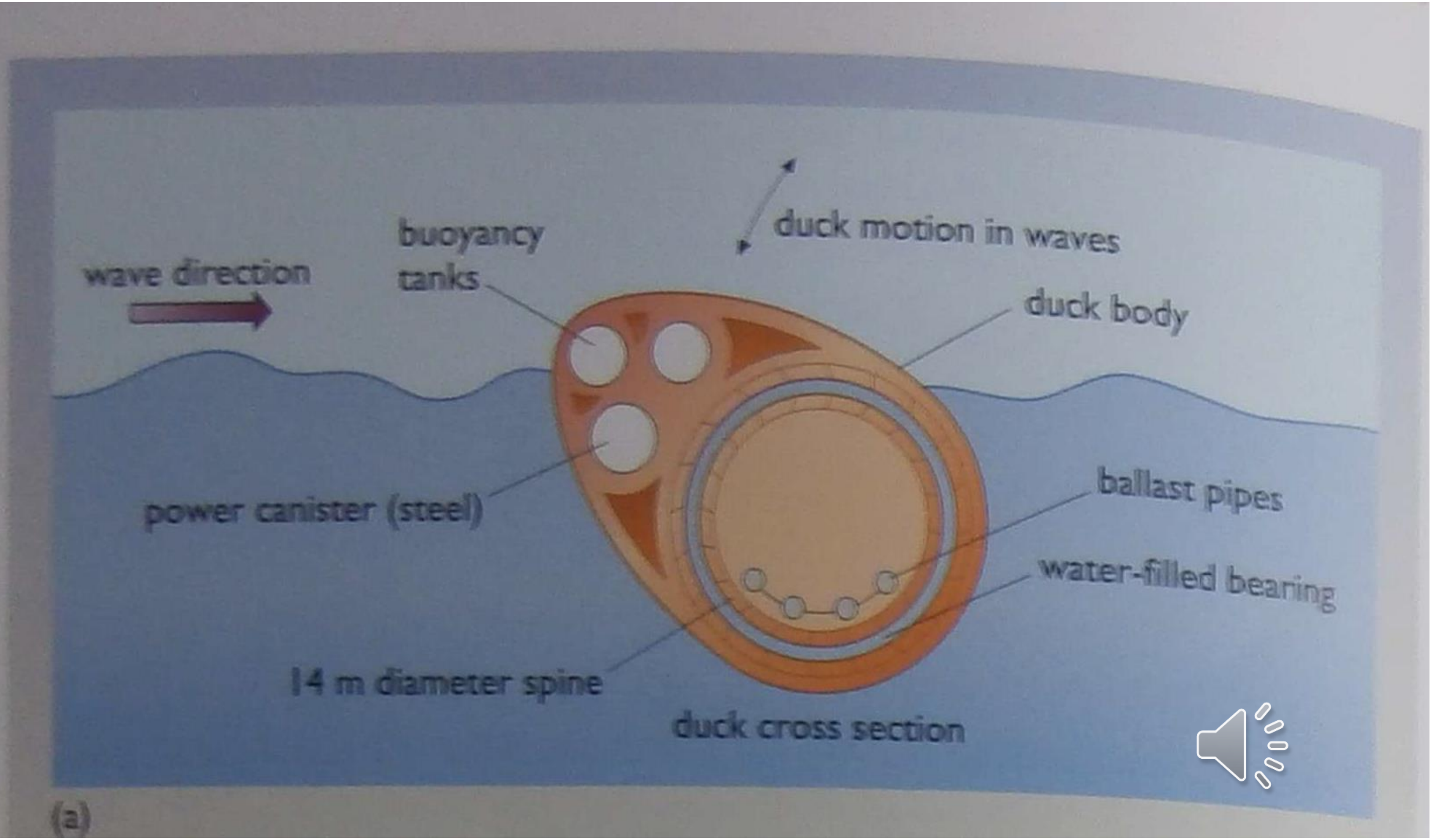


Figure 8.28 The Backward Bent Duct Buoy (BBDB)

Figure 8.29 Ocean Energy buoy with Wells turbine (courtesy of Ocean Energy)



duck motion in waves
buoyancy tanks
wave direction
duck body
power canister (steel)
ballast pipes
water-filled bearing
14 m diameter spine
duck cross section
(a)

(b)

(c)

Figure 8.32 (a) The Edinburgh Duck wave energy converter; (b) Duck model being tested in a wave tank; (c) A scale model of the Duck being tested in Loch Ness, Scotland by Coventry University

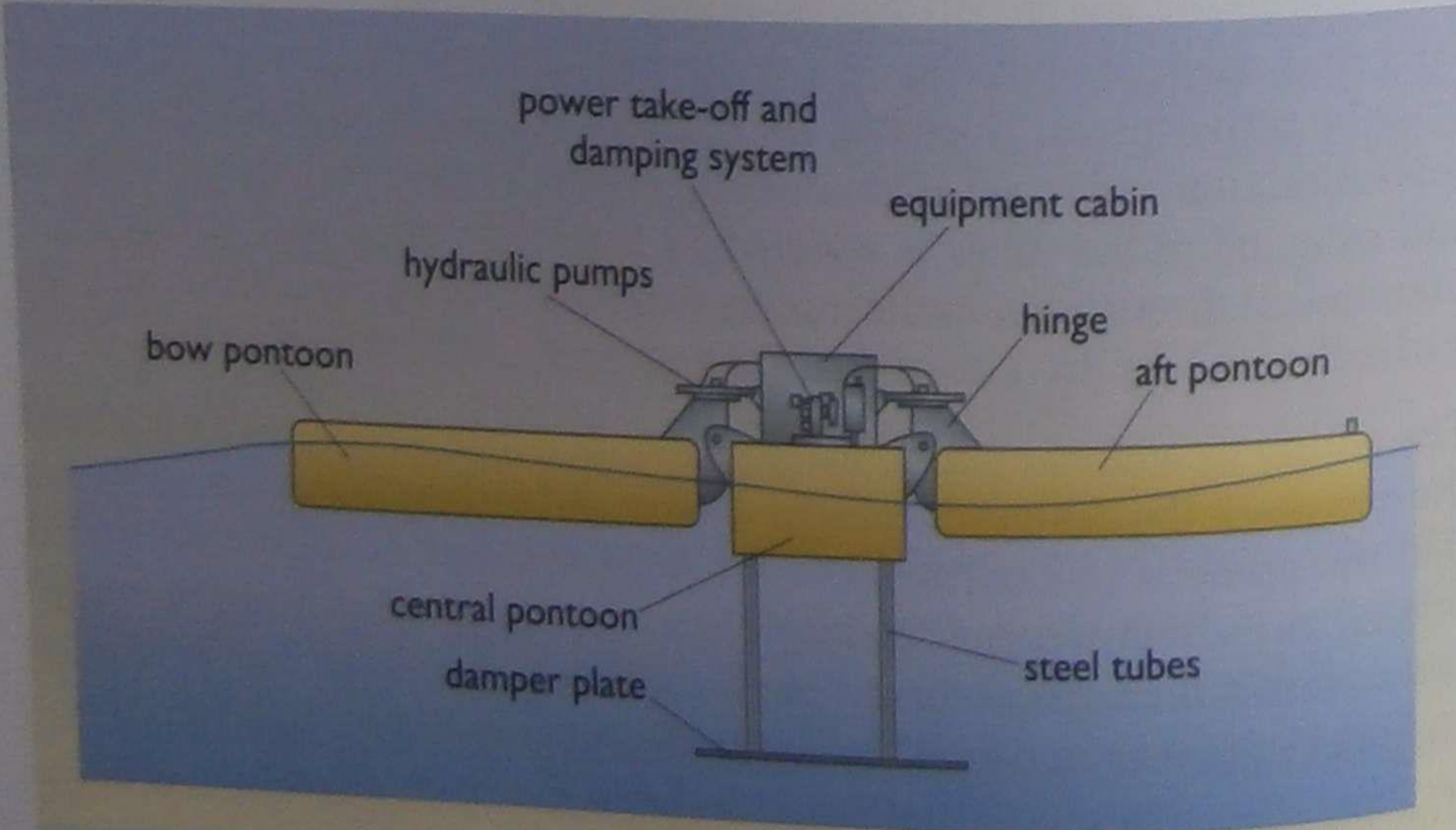


Figure 8.35 The McCabe wave pump – schematic showing operation

By careful overall design of an integrated scheme, a remote community could enjoy significant gains in electricity supply from a wave energy scheme. If this produces most of the energy the reduction in diesel oil consumption would be substantial, and since it is costly to transport diesel oil to remote locations, the cost savings could be large. Ideally the diesel generator would be held in reserve and only brought into use when the wave activity is too low to meet demand. An energy storage system such

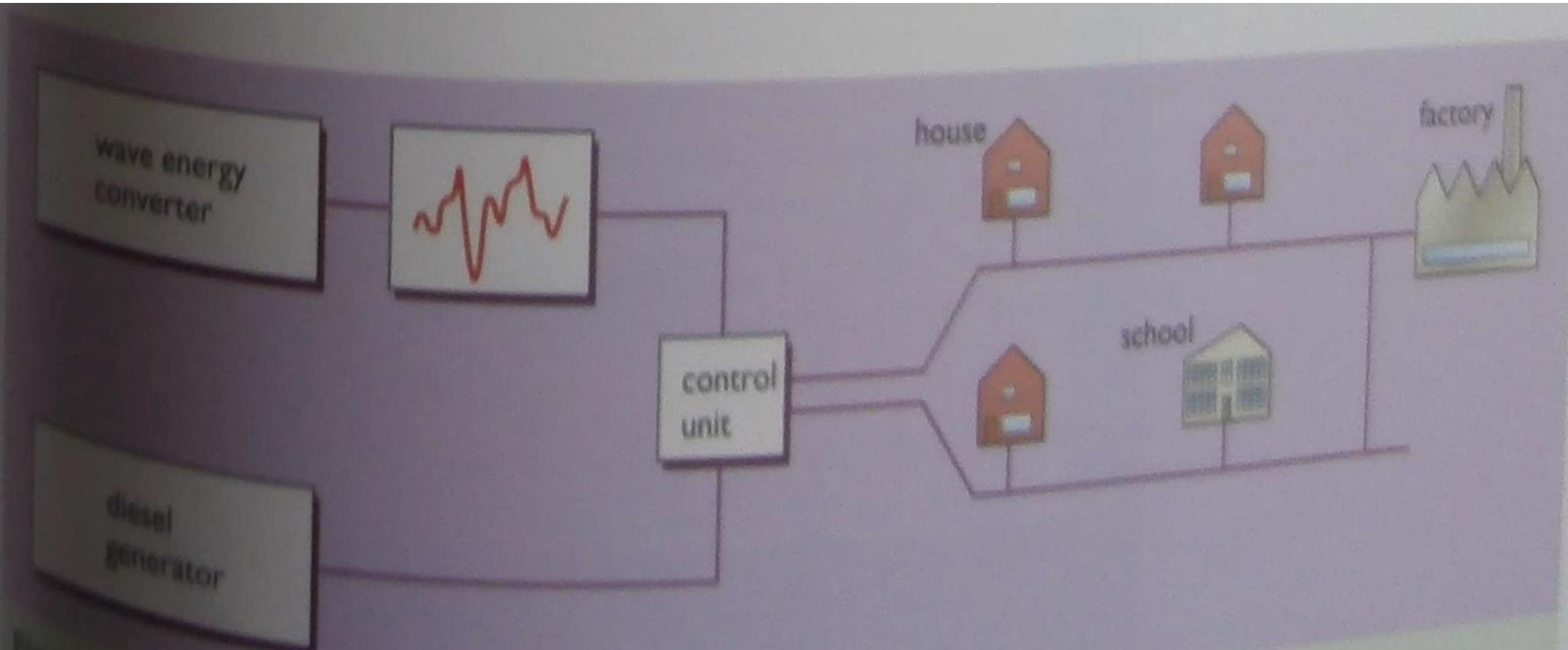


Figure 8.37 An integrated wave energy/diesel system

Wave energy for large electricity grids

When the electrical outputs of several wave energy units are added together, the total output will be generally smoother than for a single unit. If we extend this to an array of several hundred floating devices, then the summed output will be smoother still. In addition, any fluctuations in output will be less important if the electricity is to be delivered to large national systems like those of the UK, where in most locations the grid is 'strong' enough to absorb contributions from a fluctuating source. Figure 8.38 illustrates a typical scheme.

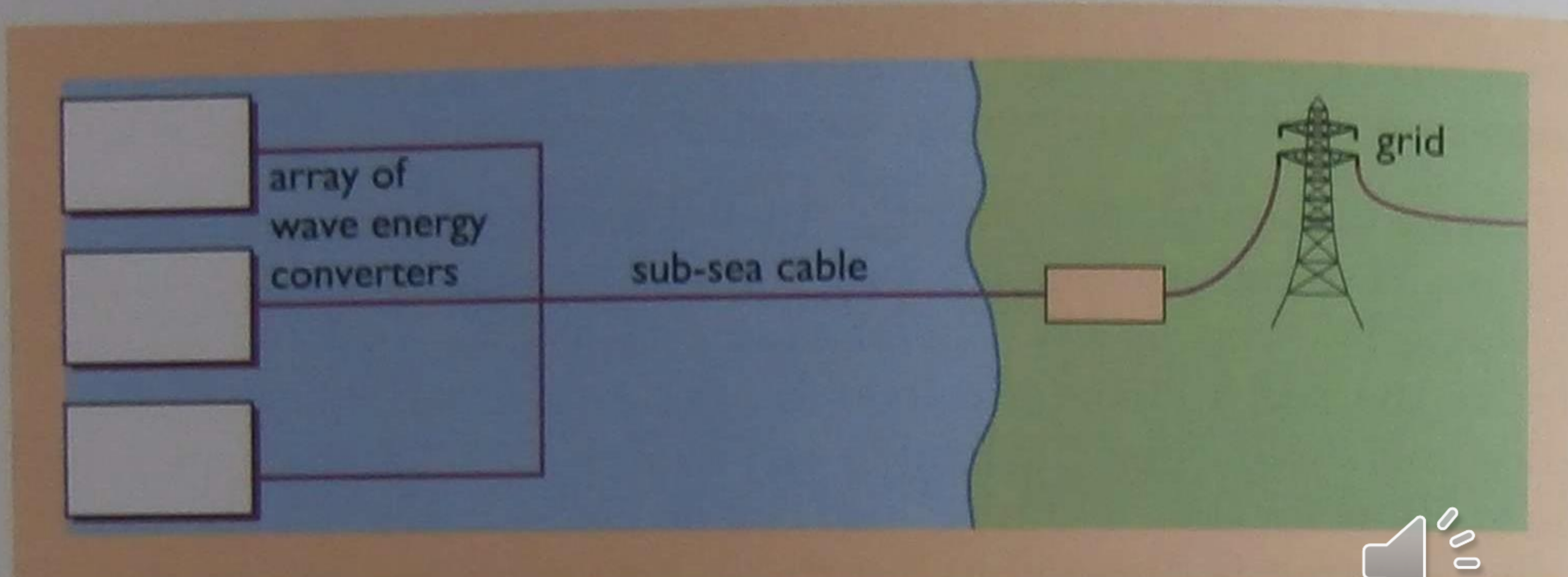


Figure 8.38 Electrical connections for an array of wave energy devices