JOURNAL OF MATERIALS SCIENCE 15 (1980) 1337–1363

Review
Materials aspects of wave energy converters

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There is current interest in renewable energy sources and the United Kingdom is favourably located with respect to wave energy. This review describes briefly the device concepts being pursued in the Department of Energy Programme and considers the materials aspects of full-scale Wave Energy Converter (WEC) development. Emphasis is placed on generic problems rather than areas specific to individual devices. Present estimates put the cost of WEC development relatively high. Thus, effort in the future will be directed at reducing these costs, particularly those of the main structure and mooring system, and the optimum use of materials will be essential. In certain areas gaps in existing materials technology have been identified and experimental programmes initiated.

1. Introduction

Following the sudden increase in oil prices in the early 1970s there was renewed interest in alternative, renewable, sources of energy. In 1974 the Government initiated an assessment at the National Engineering Laboratory (NEL) of the possibilities of large-scale energy extraction from sea waves around the UK coastline. Based on the results of this initial review, further development and feasibility work was started in 1976, centred around four main devices identified as most promising. Since that time other devices have been considered and at the time of writing two of these have also been included in the Department of Energy Programme [1]. As the programme proceeds it is hoped to decrease the number of different devices pursued until an optimum is identified for full-scale prototype development.

Wave energy derives from the solar energy reaching the earth and is accumulated on open water surfaces by the action of winds. Britain, at the eastern side of the open Atlantic, is well situated with respect to the amount of wave energy available off a significant length (several hundred km) of the coastline. Early estimates of a yearly average of $70\,\mathrm{kW\,m^{-1}}$ of wave front are now considered to be about a factor of 2 too high. These were based on data from weather station *India*, out in the Atlantic, whereas more recent estimates are based on data from experiments near S. Uist. Theoretically, one is not limited to a single line of Wave Energy Converters (WECs) since the wave energy beneath the winds can be collected every 25 km or so. However, as yet, only devices operating as close to the shoreline as possible have been considered in any detail.

Brief descriptions of the six devices being investigated and their state of development are presented in Section 2. In addition to work on specific devices, the Wave Energy Programme is supporting additional work necessary for the development of WECs, such as the accumulation of wave data from relevant sites and the development of systems for generation and transmission of power. One area of additional work is the assessment of likely materials problems to be overcome in WEC development and the present paper reviews this assessment to date, in Sections 3 and 4. Although the various devices described later have very individual features, they also have many aspects in common and many of the likely materials problems are generic in nature. For example, most of the devices comprise very large floating pieces of machinery which are intended to be moored in a most aggressive environment for long periods of maintenance-free operation. If gaps exist in our technology which prevent this being achieved we must either set work in motion to fill

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these gaps or abandon the concept of floating Wave Energy Converters. Those who suppose that no significant problems exist should consider the analogy of a supertanker moored sideways on to the prevailing seas for 30 years. Allied to the straightforward survival of WECs is the cost of construction and maintenance. Present estimates indicate that structural and mooring costs must be reduced to make extraction of Wave Energy a viable proposition. Materials requirements will thus be even more stringent than originally supposed and the behaviour of candidate materials in the operating environment must be known and understood. Several areas where technological gaps exist will (as described in Section 3) require long-term experiments and so it is not too soon to carry out a materials assessment and start these experiments despite the relatively early stage in the development of the devices. The assessment of materials aspects of WECs is aided by several current research programmes such as *Concrete in the Oceans* [2] and the United Kingdom Offshore Steels Research Project [3] and will be helped by some of the proposed experiments sponsored by the Science Research Council's Marine Technology Directorate [4]. Similarly, work done as a consequence of the materials assessment will find application in other offshore areas such as the design of tethered buoyant platforms.

2. Wave Energy Converters

In the preliminary NEL survey of ideas for extracting wave energy four main schemes were considered. Since no single method or device could be identified as significantly more attractive than the others, all four concepts were pursued in the next stage of the programme. The devices based on these concepts rely on variations in the slope and height of travelling waves in their operation. Two of the devices, the Salter Duck and the Cockerell Raft, utilize the low-velocity, high-torque, relative motion of large floating bodies as the basis of primary power take-off. In the Oscillating Water Column and the Rectifier, small heads of water drive air and water turbines, respectively. Of the two devices most recently added to the programme, that designed by Vickers is a form of oscillating water column intended to operate below the surface, possibly on the sea bed, and the Lancaster Flexible Bag is a floating device with a submerged hull supporting flexible air-filled bags, energy being extracted via low-pressure air turbines. The floating devices are currently designed to operate at around the 50 m contour and the others would sit on the sea bed at around the 15 m level.

Schematic diagrams of early versions of the original four devices are presented in Fig. 1 and of the two more recent devices in Fig. 2. The mode of operation and main components of the devices are described below. Additional components necessary when groups of WECs are incorporated into a single "power station" are also described. More detailed descriptions may be found in the proceedings of a recent conference [1].

2.1. The Salter Duck

The Salter Duck is perhaps the most complex WEC although it is elegant in concept. The essence of the device is a long floating cylindrical spine around which rotate a series of cams or 'ducks'. The spine is sufficiently long that random motion of the ducks overcomes the tendency of individual ducks to rotate the spine. Power is extracted from the relative motion of ducks and spine. In current full-scale designs the spine would be about 15 m diameter and the ducks about 20 m wide and the optimum torque about 1 MNm/metre of wavefront. Several power extraction schemes have been considered and rings of hydraulic pumps feeding a high pressure (2 to 10 MPa) main has been the most favoured by the engineers. A novel idea currently being pursued by Mr Salter is the use of high-speed gyroscopes located in every nodding duck. Accurate location of ducks on the spine is thought impractical by some and so systems using racks and gears seem unlikely. Some designs use rubber tyres to both locate the ducks and drive the oil pumps. The most serious design problem of the device remains the long spine. Rigid spines would require too large diameters to accommodate operational stresses and current thoughts are directed towards shorter (500 m) lengths of flexible spine articulated so that the joints remain rigid in moderate sea conditions.

Research to date on small-scale models in wave tanks has optimized the duck profiles for efficient power extraction in different wave spectra and for 'safe' operation in violent seas and breaking waves. Tests on a 1/10th scale model in Loch Ness are also producing useful data on loadings as well as energy extraction efficiencies. Steady state mooring forces for a full-scale device are likely to be in the region of 2 tonne/metre of wavefront. None of

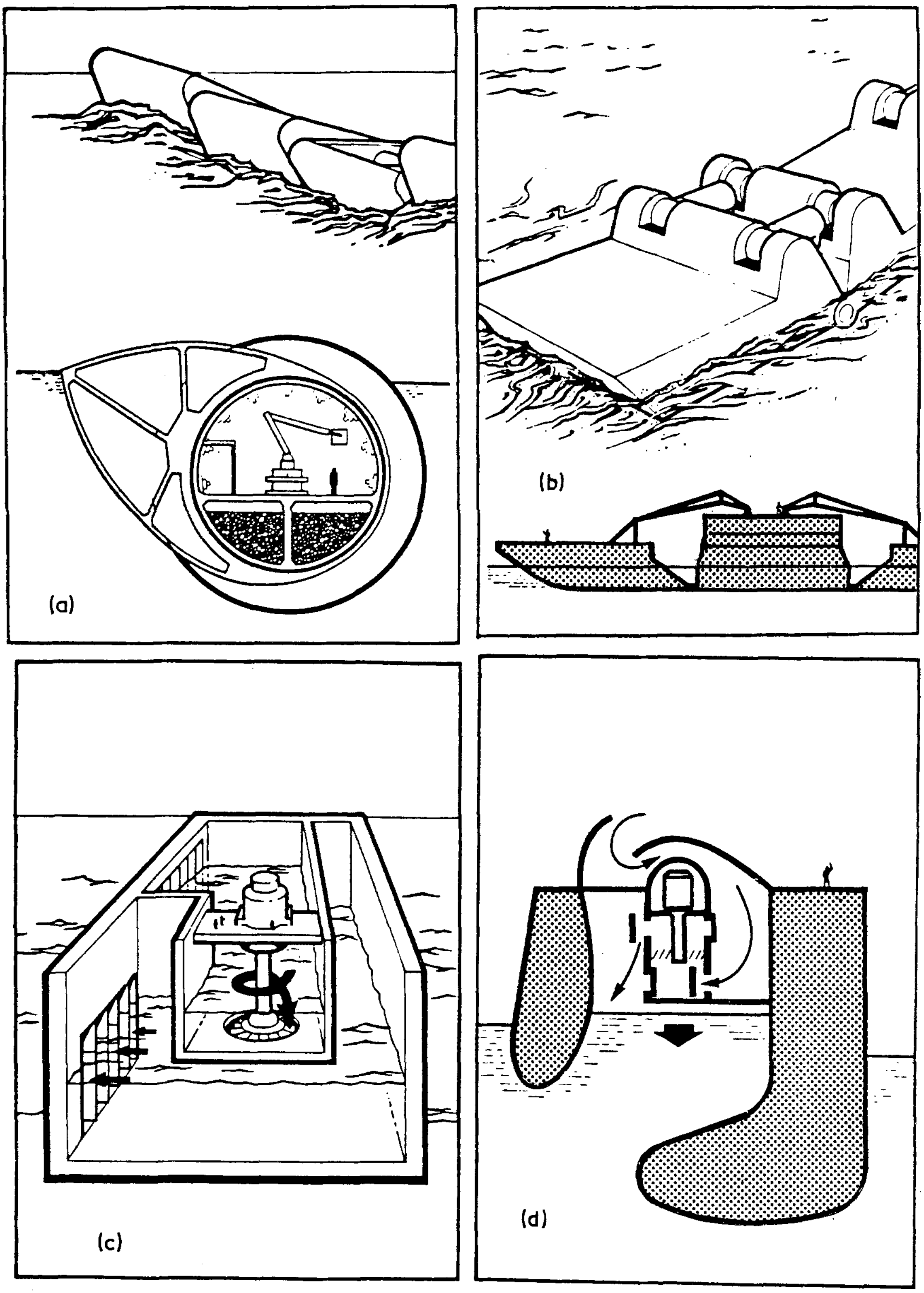


Figure 1 Schematic diagrams of original four Wave Energy Converters (a) Salter Duck; (b) Cockerell Raft; (c) Russell Rectifier; (d) NEL Oscillating Water Column.

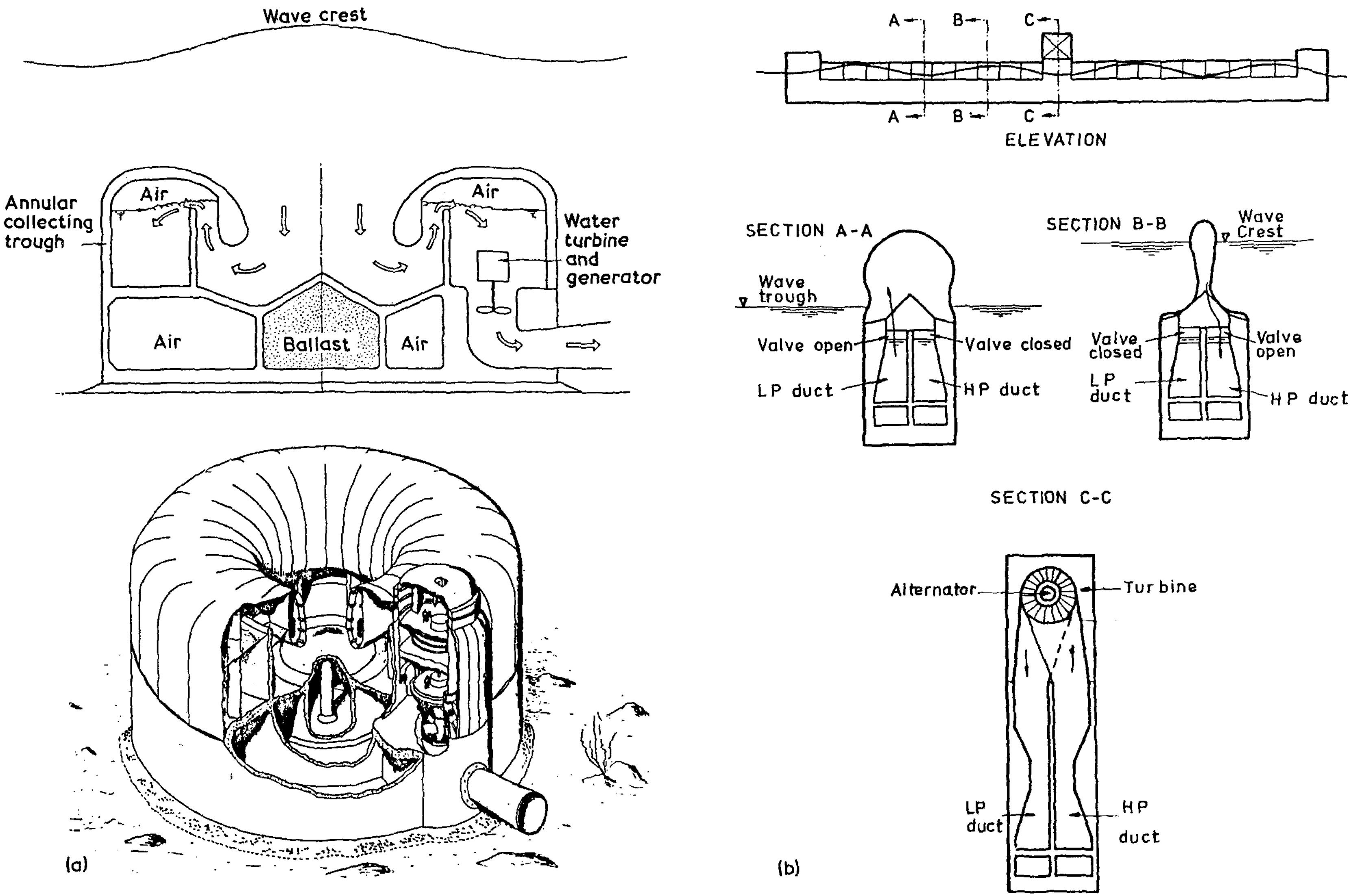


Figure 2 Schematic diagrams of mode of operation of (a) Vickers Device, and (b) the Lancaster Flexible Bag Device.

the model tests to date have included materials of likely use in full-scale devices.

2.2. The Cockerell Raft

This device consists of two or three shallow pontoons connected by hinges and some form of power extraction system. As in the Duck, energy is transferred by the slow relative motion (high torque) or large floating bodies, in this case the hinged pontoons. At full scale a typical individual device would be about 50 m x 100 m and 5 to 10 m deep and rated at 1 MW. The favoured primary power take-off system is a seawater hydraulic one in which loss of damping could be readily accommodated. Both high (2 to 10 MPa) and low (0.1 to 0.5 MPa) pressure systems are being considered at present. Several mechnanical linkages are being considered such as gear drives and cranked ram arrangements. Closed fresh water systems with double-acting bellows pumps are also being considered.

As with the Duck device the Cockerell Raft has reached the stage where $\frac{1}{10}$th scale trials, in this case in the Solent, are supplementing the smaller model tests in wave tanks. Raft design is still evolving, particular emphasis being directed towards minimizing effects of "wave slamming" on the leading pontoon. Mean mooring forces in the range 1 to 10 tonne m^{-1} of wavefront are predicted for full-scale devices. As with all the moored devices, instantaneous forces of up to ten times this value must also be taken into account.

2.3. The Oscillating Water Column (OWC)

Small-scale navigation buoys have been powered on the principle of a vertical column of oscillating water in tune with the oncoming waves and the OWC represents an extension of this idea to WEC design. In the present device a water column oscillates a column of air above it and drives air through rectifying valves and a turbine. The device requires the large inertia of the floating structure and current full-scale designs envisage units about 150 m x 40 m x 50 m containing nine 15 m x 15 m water/air columns and three 2 m diameter air turbines running at several hundred rpm with a pressure difference of about 10 kN m^{-2}. Such a system could be designed on the basis of known technology but development work is needed to overcome possible problems associated with water ingress into the air turbines. Ideas for air rectification valves include the use of pressurized rubber balls on stainless steel seatings.

Until now model tests have been limited to ~ $\frac{1}{100}$th scale in wave tanks to optimize the geometry of the device but $\frac{1}{10}$th scale tests are currently being considered. Mean mooring forces of up to 10 tonne m^{-1} of wavefront are envisaged for full-scale devices.

2.4. The Rectifier

The Rectifier is a large seabed-mounted device sitting in about 15 m water in whose primary power take-off is a series of conventional low-head Kaplan turbines. A single unit comprises a large caisson with upper and lower sea water reservoirs connected via the turbines. Water enters the upper reservoir through flap valves as a wave crest meets the device and leaves the lower reservoir into a wave trough, again through flap valves in the front face of the device. An individual unit in a full-scale device is envisaged as 100 m long with a peak 3 MW output.

The device has been tested at $\frac{1}{30}$th scale in wave tank tests and current emphasis is on reducing the size of the very large structure and optimizing the design of the flap valves and hinges. It has the significant feature of avoiding the mooring problem but the total length of available sites for this seabed-mounted device is considerably less than that available to the floating devices.

2.5. The Vickers Device

This is essentially a submerged oscillating water column extracting power via a water turbine working with unidirectional flow. A submerged tube is attached to a closed air reservoir at one end and is open to the sea at the other. As surface waves pass over it, pressure changes cause water oscillation and resonance. Water can then overspill to raise the level in the reservoir. To maintain the original reservoir level water is allowed to drain off through a turbine. In practice, inflow and outflow can be balanced to produce a steady flow through the low-head turbine. No details of how big a full-scale device might be are yet available, but in general the size will be determined by the volume of air which provides the restoring force for the oscillating water column.

2.6. The Lancaster Flexible Bag

The design of this device comprises a series of air-filled bags on a submerged (~ 15 m) hull lying head-on to the sea. Individual bags could be formed by partitioning a long flexible tube with flexible membranes. In a full-scale device the hull is envisaged to be about 6 m wide 200 m long and 8 m deep for an output of several MW. As waves run along the converter the rise and fall of water on each side of the bags causes the latter to act as bellows pumping air from low- to high-pressure ducts; the differential pressure is about 15 kN m^{-2} in practice. Power is extracted by air turbines operating across this pressure difference. As with the Vickers device, this WEC is at a very early stage of development and optimization. It is, however, considered promising in that construction costs may be relatively low and mooring relatively easy since the device is not "sideways on" to the waves.

2.7. Ancillary equipment

In any practical application, groups of WECs would operate as a "power station", for example a 2 GW complex off the Outer Hebrides. Present schemes are based on groups of converters with a total output of about 200 MW feeding a.c. current to platform-based transformer/rectifier stations which, in turn, feed d.c. current to on-shore inverter stations. Electrical generation on individual devices is envisaged with conventional 2 MW synchronous alternators. Devices and platforms will be linked by flexible a.c. cables of which 33 kV is the maximum rating currently available and conventional 250 kV d.c. submarine cable will link platform and shore. In assessments to date, underwater transformer stations have been excluded as more expensive and technically more difficult to build and maintain than platform stations.

Electricity transmission to shore is not the only option available in a WEC system. Hydraulic fluid could be pumped to shore before conversion so removing the generation and conversion equipment from the hostile marine environment. Alternatively chemical products, based on the *in situ* electrolysis of sea water, could be produced and transmitted. So far, the electrical option seems to be the cheapest and in the remainder of this paper no discussion will be given of materials problems to be met in desalination and electrolysis equipment or other equipment involved in developing the other options.

2.8. Summary of major components

Before discussing the behaviour of available materials in the marine environment of likely WEC operation, we summarize the major components of the WEC systems. These components are listed in Table I. In Section 3 the materials phenomena relevant to the choice and development of materials for these components are discussed with particular emphasis on gaps in our knowledge and understanding.

TABLE I Major components of WECs

Main hull
Mooring system
Primary power take-off
Hydraulic systems
Hinges and bearings
Seals
Valves and flap gates
Turbines and generators
Flexible power cables

3. General materials aspects

Many of the potential materials problems facing WEC designers are well known from other areas of marine technology. In particular, corrosion of metals in sea water and splash-zone environments have been investigated in great detail and the means of overcoming these problems are available, if not always adopted. The main phenomena likely to cause problems for WECs are listed in Table II. Different problems will dominate different areas of the devices but there are several areas where generic problems will exist, for example, corrosion fatigue. The phenomena listed in Table II do not occur independently and several gaps in our knowledge and understanding centre around complex interactions such as the combined effects of marine fouling and corrosion.

In the remainder of this section the main aspects of likely material problems are reviewed briefly and their interaction with major WEC components is discussed in Section 4.

3.1. Corrosion and corrosion fatigue

Almost all common engineering metals and alloys are corroded in marine environments, and it is inevitable that corrosion resistance and corrosion prevention will be a vital factor in determining

TABLE II Main materials phenomena affecting WECs

Corrosion
Fatigue
Corrosion fatigue
Stray current corrosion
Wear and fretting fatigue
Marine fouling
Impact loading and fracture

the durability of Wave Energy Converters. There is a vast experience of the behaviour of metals in marine environments, a good understanding of the mechanisms of corrosion, and reliable methods of overcoming corrosion by alloy selection, coating or cathodic protection [5]. Nevertheless, the correct application of known technology of corrosion prevention is very difficult to achieve and current practice in the manufacture of large devices for marine applications rarely, if ever, achieves the corrosion protection which will be essential for WECs.

Although sea water chemistry in the open oceans does not vary widely from one part of the world to another, there are differences in dissolved oxygen concentration, pH, temperature, wave action, solids in suspension and marine growth on surfaces which can affect corrosion rates profoundly. It is not surprising, therefore, that experience has shown wide variations in corrosion behaviour under nominally similar corrosion conditions, and the gathering of corrosion and marine fouling data at proposed sites for WEC location will be an important preliminary before many design decisions can be made.

Metals and alloys corroding in marine conditions can be broadly classified into two types:

(a) those, e.g. mild steel, in which corrosion rate is determined largely by the supply of oxygen to their surfaces. Highest corrosion rates are observed when both sea water and oxygen are in highest supply, i.e. in the splash and tidal zones. Increased sea water velocity may also increase corrosion;

(b) those, e.g. stainless steel, which form an adherent protective "passive" oxide film on the surface. Resistance to marine atmosphere, splash zone and flowing aerated sea water is excellent, but localized corrosion can often occur when access of oxygen is restricted, e.g. in stagnant sea water, beneath fouling or in crevices.

Copper alloys which are widely used in marine conditions, behave in a way intermediate between the above types, forming passive films which are sensitive to velocity effects, so that corrosion may depend on oxygen level in sea water flowing above a critical velocity. Localized corrosion due to turbulence, impingement or cavitation, can easily occur in flowing sea water systems unless care is taken over design and alloy selection. Fig. 3 and 4 show typical corrosion behaviour of a number of common alloys in quite and flowing sea water [5].

Because sea water is a highly conducting electrolyte, corrosion is often modified by galvanic effects, either when two metals which take up different potentials in sea water are coupled together, or when external electric currents, particularly d.c. currents, flow through the sea water from one part of a structure to another. The latter ("stray current corrosion"), can be a very important factor and difficult to eliminate in a structure carrying electrical equipment, and the role of WECs in the generation of electricity may focus attention on the as-yet not fully understood effects of stray a.c. currents on corrosion. The "Galvanic Series" for sea water (Fig. 5) is a guide to possibility of corrosion when different alloys are coupled together, but the relative areas and resistivity of the galvanic circuit as well as potential difference will determine whether corrosion can be seriously enhanced. The interaction between corrosion and mechanical factors can be extremely important, and stress (applied or residual, constant or cyclic) vibration and fretting can all influence corrosion behaviour.

The limitations of alloys known to be susceptible to stress corrosion cracking or hydrogen embrittlement in sea water under a constant applied stress are generally understood and can be taken into account by designers. However, the influence of corrosion on fatigue endurance, and the interaction between fretting and corrosion are less well documented. The data for ferritic steels, arising from work stimulated by the needs of the offshore oil industry, are quite good [7]. In particular, the effects of stressing frequency and cathodic protection on crack growth, which assumes a greater importance than crack initiation for welded steel structures, has received attention but the possible influence of marine fouling has not yet been fully explored. The corrosion and corrosion fatigue behaviour of weldable structural steels used in the offshore platform industry have been reviewed recently by Sharp [8] and it is unnecessary to repeat the exercise here. Of particular relevance to WEC design and operation are the results of Scott *et al.* which show how in the corrosion fatigue environment crack growth can be up to six times faster at frequencies typical of wave loading (~ 0.1 Hz) than at higher frequencies [7]. The corrosion fatigue behaviour of steel wire ropes is thought to be a critical area where more work is needed for the assessment of mooring system design, as discussed further in Section 4.2. Although a significant amount of

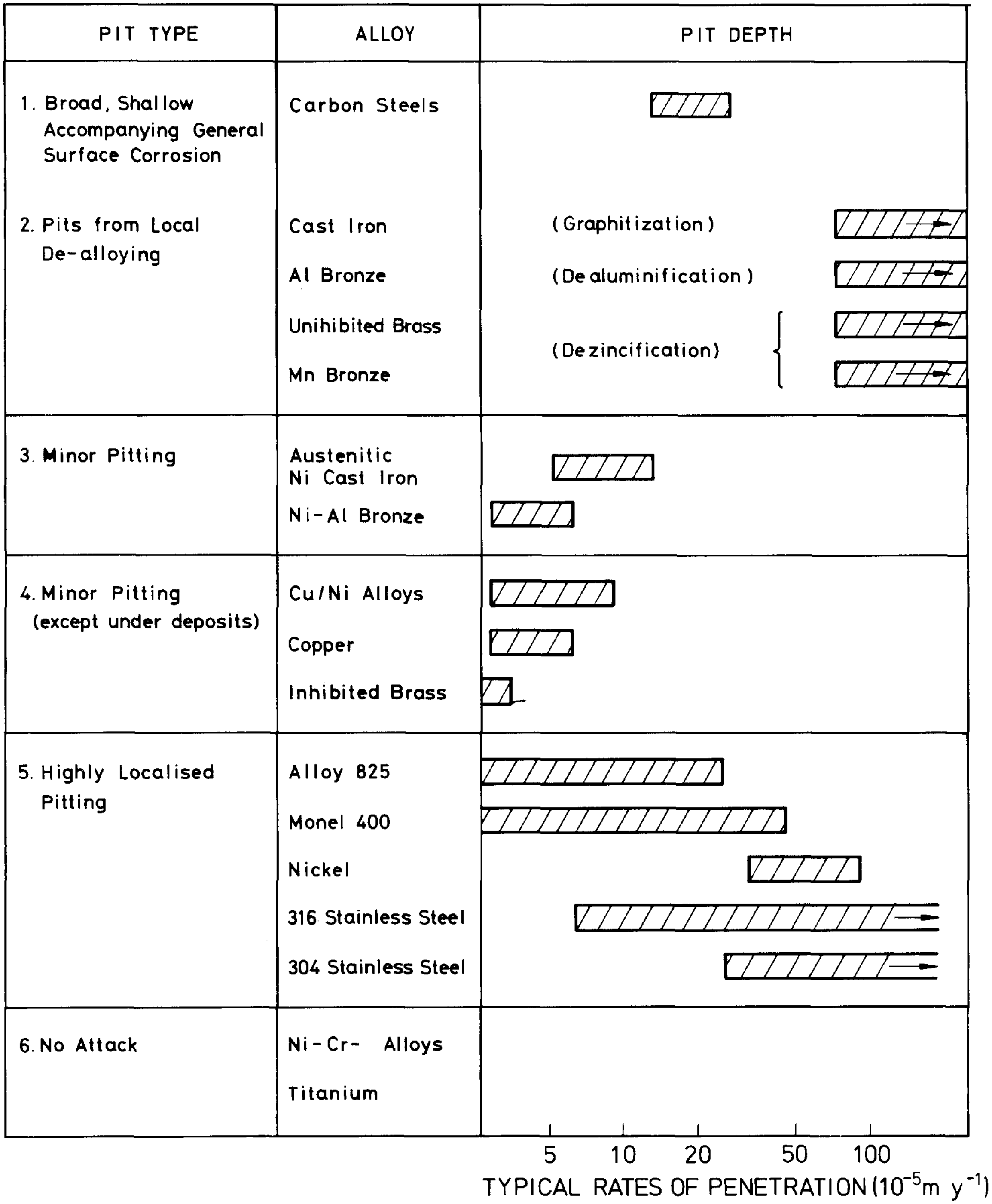


Figure 3 Rates of pitting in quiet sea water [5].

data are being gathered, little attention has, as yet, been given to the physical metallurgical aspects of corrosion fatigue and there is scope for work in this area in the future. There is a considerable amount of data on fatigue endurance of stainless steels, but little of direct relevance to WEC applications, while data on copper alloys and titanium are sparse. It can be broadly concluded that good corrosion resistance, particularly to localized corrosion, is likely to improve corrosion fatigue by prolonging the fatigue crack initiation stage, but it is clear that the corrosion fatigue properties will have to be determined for any particular alloy selected for use where it will be exposed to the

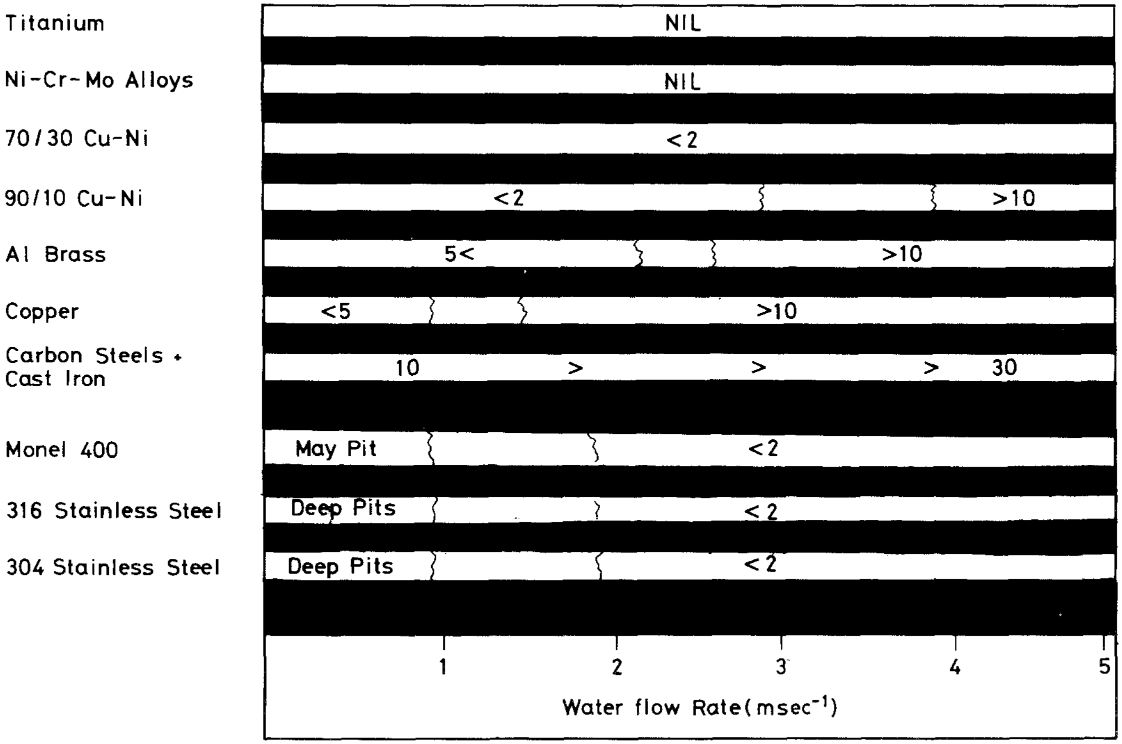


Figure 4 Rates of pitting in flowing sea water (10^{-5} m y^{-1}) [5].

marine environment and subjected to variable stresses.

A great deal can be done to minimize corrosion by the best use of materials and design. Proper use of materials include the choice of corrosion-resistant alloys, recognizing their susceptibility to particular forms of corrosion, specifying correct heat treatments, fabrication techniques and production methods, thorough inspection and quality control. It may also, of course, include the use of non-metals where their properties and economics make them a satisfactory alternative to metals. Design against corrosion includes minimizing galvanic corrosion problems, recognition of stress corrosion and corrosion fatigue limitations and avoidance of crevices on many "passive" alloys.

The two principal corrosion protection methods are protective coatings and cathodic protection. Modern marine organic coatings, usually applied to steels, are highly effective if applied to well prepared surfaces and should give protection for 10 years or more in the absence of mechanical damage. For submerged surface, cathodic protection is frequently used as an addition or alternative to coatings, taking advantage of the reduction of corrosion at a cathode either by attaching "sacrificial anodes" of, for example, zinc or aluminium to steelwork, or by means of an external "impressed current" system. Zinc coatings (galvanizing) or zinc-rich paints can serve a double purpose of direct and galvanic protection and are frequently used in atmospheric conditions as undercoatings to minimize corrosion beneath organic coatings in the event of mechanical damage.

3.2. Fracture

In addition to the constraints imposed by fatigue and corrosion fatigue, resistance to impact damage and fast brittle fracture must also be taken into account in WEC design. As reviewed by Sharp [8], the correct use of selected steels and designs should obviate brittle failure in large welded steel structures. Prolonged exposure of large steel structures to the sun on one surface and the sea on another, could lead to strain ageing effects which would reduce toughness for subsequent winter operation. The factors controlling the toughness of welds in large steel structures are not well understood, although research is continuing in this area. Of particular interest for the design of large floating structures is the toughness and integrity of welds in chains (Section 4).

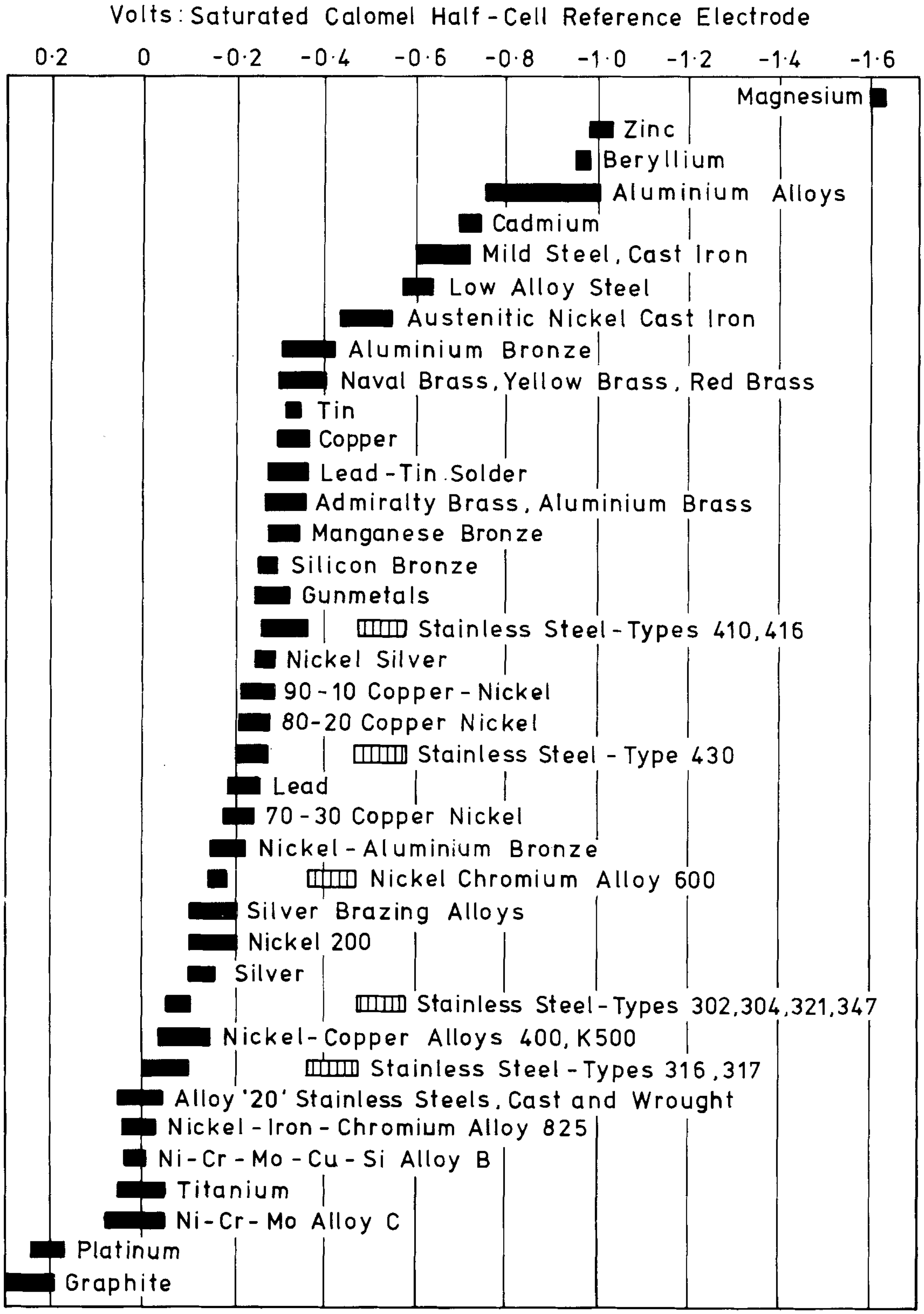


Figure 5 The galvanic series of metals and alloys in flowing sea water [6].

3.3. Marine fouling

The settlement and growth of marine plants and animals (fouling) on several types of structure has been investigated and documented for many years [9]. Antifouling measures have also been developed to deal with specific situations; in particular antifouling paints in current use keep metal ships free of barnacles for up to 2 years. The type and amount of fouling depends on many parameters including the type of structure and its location. It was wrongly assumed, for example, that the North Sea would be an inhospitable place for fouling and only recently has the increase in dimensions of structural members of oil and gas platforms due to fouling been recognized as a serious problem. Wave Energy Converters present a new type of structure with novel operating conditions and it is necessary to assess at an early stage how they may be affected by fouling and what can be done about it.

3.3.1. *Main characteristics of fouling*

Fouling is important for several working structures because of one or more of the effects listed in Table III. The amount of fouling developed on a structure is sensitive to its location. Thus the data available from many locations (mostly around the United States) can only give a rough guide to the magnitudes involved. Even then there are really only reliable data for barnacle and mussel fouling. Table IV lists maximum fouling rates observed after relatively short times on moored structures.

From the measured fouling rates at different locations and temperatures [9], we estimate that the total hard fouling (relative density 1.4) build up on WECs off the Outer Hebrides could be 40 to 50 $\mathrm{kg\,m^{-2}\,y^{-1}}$. Such increases are unlikely to occur over many successive years and so the loss of bouyancy over this time can only be estimated very roughly. Of the floating WECs the Salter Duck and the Lancaster Flexible Bag are the only ones likely to be embarrassed by straightforward weight increase due to marine fouling.

TABLE III Possible effects of marine fouling

- Increased weight of structure
- Increased volume of structure
- Increased surface roughness
- Increased drag coefficient
- Blockage of pipes, conduits, valves and gates
- Changes in corrosion rate and mechanisms
- Changes in corrosion fatigue life
- Changes in brittle fracture probability
- Reduction in heat transfer efficiency of condensers
- Tribology effects on moving parts in contract, e.g. reduction in wear life of bearings
- Masking of surfaces obviating routine inspection and maintenance

TABLE IV Maximum fouling rates measured in year tests

Navigation buoys	54 $\mathrm{kg\,m^{-2}\,y^{-1}}$	mussels (dry)
	30 $\mathrm{kg\,m^{-2}\,y^{-1}}$	barnacles (dry)
	40 $\mathrm{kg\,m^{-2}\,y^{-1}}$	kelp (wet)
Chains (50 m diameter)	23 $\mathrm{kg\,m^{-1}\,y^{-1}}$	

There is much evidence suggesting that certain surfaces are less prone to fouling than others. Care is needed in interpreting this evidence for two reasons. In the first place a lot of the evidence is from short-term exposures and in the few tests where prolonged exposure was allowed it was generally discovered that the final fouling community build-up was independent of the slow initial rates. Secondly, comparative tests can in themselves be misleading. Thus, if a light and dark panel are available for fouling more build-up will usually be found on the dark surface in the short term. However, if no dark surface were available, the fouling with its innate driving force to settle would readily accept the light surface, given no alternative.

Most marine structures contain protected metal and so the effect of fouling on the protection is more relevant than the effect on bare metal. Barnacles and other hard fouling are known to penetrate paint films and cause local loss of protection and enhanced corrosion. Enhanced local corrosion and corrosion fatigue could be more deleterious than smaller overall corrosion rates. This fact has been recognized by the United Kingdom Offshore Steels Research Project [3] and future tests to include the effects of fouling on fatigue of welded steel joints are being designed. The interaction of marine fouling and cathodic protection systems has not been fully investigated. There are references to both enhanced and decreased settlement on protected components and there is a need for more systematic studies in this area. Examples are emerging of localized corrosion under fouling on apparently cathodically protected members of offshore structures. Fig. 6 shows an example of significant corrosion below marine fouling on cathodically protected structural steel.

3.3.2. *Antifouling treatments*

The procedures currently employed or proposed to overcome problems of fouling are listed in

Figure 6 Example of enhanced corrosion on cathodically protected structural steel below marine fouling.

Table V. The state of the art with respect to mechanical removal of fouling from protected or unprotected surfaces has been reviewed by Freeman [11]. Such a solution to the fouling of WECs cannot be ruled out at this stage until we know (i) the fouling rates in the appropriate location, and (ii) the economically viable maintenance routines involving towing floating devices to calm waters or even dry docks. Nevertheless, specific components of the devices will have to be kept free of fouling and some or all of the alternative methods will find application.

Chlorine injection combined with coatings of antifouling paint is standard practice in power stations pumping sea water [12]. A typical 2000 MW (e) station needs 5 to 6 x 10^7 gal h^{-1}. To overcome mussel and barnacle fouling, continuous injection of 0.5 to 1.0 ppm chlorine is used and in 1976 the CEGB used 70% of the 1500 tonnes of chlorine used for biocidal purposes in the UK. In addition, screening of larger fouling is essential. For example, at Fawley 3 to 5 x 10^3 kg of seaweed is screened every week. Wylfa power station has been completely blocked by kelp blown up in Autumn storms.

Antifoulding paints have restricted life simply because they release continuously their toxic ingredients. Barnacles are the hardest to overcome and leaching rates of about 10^{-1} g m^{-2} day^{-1} are required for protection. Unlike chlorine, the toxic substances effective in antifouling paints are undesirable environmentally. It is doubtful whether the antifouling treatment presently given to ships could have large scale application since its success relies on regular cleaning of surfaces and replenishment (~ every 2 years). However, there is a large commercial incentive to improve ship antifouling paints and results are beginning to be encouraging for longer term use [3]. As yet little attention has been given to the application of antifouling paints to reinforced concrete structures.

Cladding material is finding more application to counter fouling in marine technology. The general use of such coatings seems too expensive at present but until the costs of WEC maintenance are more accurately assessed it cannot be ruled out. The possibility of controlling fouling with hot water (> 50° C) or steam is being considered for certain North Sea platform applications and the method should be equally applicable to WECs as an alternative to straightforward mechanical removal.

3.3.3. Fouling in WEC locations

Although there are data on marine fouling for a number of locations around the British Isles and a substantial amount of additional information is emerging from operational experience with oil and gas platforms in the North Sea, no data exist for regions west of the Outer Hebrides which is a favoured location for future WECs. Modest tests are now being carried out by the Scottish Marine Biological Association (SMBA) in a location 10 miles west of South Uist and experiments initiated by Sea Energy Associates are being conducted near the Isle of Shona. The latter tests are aimed at investigating the bonding properties of several coatings to concrete and the relative antifouling properties of the different coatings. The SMBA

TABLE V Antifouling procedures

Type	Examples	Structures
Removal of fouling	Manual, mechanical (hydraulic tools retrojets)	Fixed offshore structures
Direct injection of poison	Usually chlorine compounds	Pipework, culverts, etc
Antifouling paints	Cu-base paints, organo-metallic paints (Cu, Pb, Hg, Zn containing)	Ships, pipes, culverts, etc
Antifouling cladding	Cu-based alloys e.g. (91 Cu, 10 Ni)	Test panels, some ships
Thermal treatment	Water, steam	Cooling water pipes

tests are measuring fouling build-up on standard test panels at three water depths including the splash zone. In addition, seabed surveys have identified the presence of large amounts of kelp down to depths of 25 m which includes the proposed location of seabed-mounted WECs. Future experiments will investigate the interaction between fouling and corrosion of steel test panels and the effects of cathodic protection.

4. Materials aspects of major components

4.1. Main structures

Steel and concrete are the two materials generally considered for the main structural components of WECs. There is a vast amount of experience of large structures in both materials. Concrete enjoys a reputation for providing long-term maintenance-free durability at relatively low cost, whereas steel has the disadvantage of a well understood but, nevertheless, often costly maintenance problem in the corrosive marine environment. However, the higher strength/weight ratio of steel is a major advantage over concrete in many applications, and it seems most likely that both materials will find use on a large scale in WEC construction. Reinforced plastic may find some specialist applications but, because of cost, it unlikely to replace steel or concrete for the main hull of floating WEC or the static structure of sea bottom-mounted devices. The Lancaster device is a special case were the flexible bag, which forms a major part of the structure, will probably be made from a reinforced rubber.

4.1.1. Steel

Mild steel is widely used for marine construction, with low-alloy steels finding use where higher strength is required. Steels are selected for availability, cost and mechanical properties (strength, fracture toughness, weldability [8]). Corrosion, either through (sometimes localized) metal wastage, through reduced fatigue endurance or with higher strength steels through cracking under tensile stress, is the principal cause of deterioration. Stress corrosion cracking is avoided by limiting the yield strength of the steel and by careful metallurgical control, but protection is required to avoid corrosion, and perhaps corrosion fatigue if cyclic stresses are sufficiently high. Usually protection is provided by some form of paint or other coating or, for underwater steelwork, by cathodic protection, although in special circumstances the steel may be protected by cladding with a more resistant metal.

The ideal marine coating for steel should be cheap and should adhere well to a steel substrate. It should be easy to apply and repair, resistant to the marine environment, abrasion and damage resistant, non-conducting, and it should completely exclude air and moisture from the steel surface. This is an impossible ideal and the compromise necessary to provide optimum coatings for widely different requirements has produced a vast range of products.

Inadequate surface preparation is a common cause of poor coating performance, and conditions in shipyards where final painting is sometimes carried out hurriedly on badly weathered surfaces exposed to a wet cold windy climate are a notorious cause of early coating failure. Coatings can be manufactured with tolerance to these conditions, but not yet without sacrificing performance, and high-performance paints may require the surface to be cleaned to bare metal and dry with strict adherence to specific curing times and temperatures. The emphasis, particularly in the shipbuilding industry, has long been more on cost and ease of application than on long-term performance, but WECs must be provided with a first coating system of the highest possible integrity to reduce the need for maintenance painting to the minimum. High-performance coatings are available, and in the absence of serious mechanical damage, a properly applied high-performance coating system should be expected to provide protection for at least 10 years.

The alternative of cladding steel with a corrosion resistant metal such as cupro nickel should be considered. The main danger of cladding with a corrosion resistant alloy, which will almost inevitably be cathodic to steel, is galvanic corrosion if the steel is exposed. This virtually rules out thin cladding or metal sprayed coatings which are easily damaged or porous, and the correct approach seems to be fabrication from pre-clad plate with a substantial thickness of corrosion resistant metal. This would be costly, but it is possible that large-scale use of clad steel might prove economical for WECs if it guaranteed corrosion protection for the life of the structure.

Cathodic protection is widely used for submerged steel structures, either alone or in combination with paint coatings. The protection current is supplied either by corrosion of a sacrificial anode of zinc, aluminium or, occasionally, magnesium or by an "impressed current" from an external d.c. source via an inert electrode. For WECs with electric power readily available, the advantage seems to be with an impressed current system, although improvements in reliability and control over present standards will be required for a long-life low-maintenance system. In particular, it is essential to avoid over-protection, which lowers the steel potential below the level needed to suppress corrosion. This is not only wasteful, but can damage paint coatings and, more serious in some circumstances, can increase the rate of corrosion fatigue crack growth [7].

4.1.2. Concrete

Concrete has provided a very versatile construction material, particularly in conjunction with reinforcing and/or pre-stressing steel to provide the tensile strength which it otherwise lacks. Many different types of cement have been evolved, and exploitation of the full range of concrete properties to design strong, durable and economic structures has developed a highly specialized technology. Experience which already exists of concrete marine structures (e.g. jetties, boats, ships and offshore platforms) is generally favourable. The durability of concrete in a marine environment has been reviewed recently by Sharp [8]. Problems such as fatigue and corrosion of embedded steel work are still being actively investigated, but they can be overcome by design and quality control, and it is known that the primary requirements for a durable structure are a strong, dense, impermeable, cement-rich concrete with a thick cover over embedded steel. The conditions needed to produce a satisfactory concrete are understood, in general terms, but in practice satisfactory results are usually achieved by a specification which allows a considerable tolerance for likely variations of materials and on-site production. As a result, the tight specifications set by the oil industry and the classification societies for North Sea operations, while providing some confidence in the durability of off-shore concrete platforms, have made them relatively expensive.

Concrete construction for WECs is unlikely to be economic if it is required to meet existing specifications, and the emphasis must therefore be on ways of minimizing construction costs while achieving acceptable mechanical performance and durability. It will be necessary to design much closer to material limits than hitherto, whilst not paying too high a premium in the cost of control on materials and fabrication. Failure to produce a completely satisfactory concrete is most likely to result in steel corrosion problems, and it may be necessary to accept additional protection using either coatings or cathodic protection. Cathodic protection is already becoming more widely used for steelwork embedded in concrete, and surface treatment of concrete to protect it against mechanical and/or chemical deterioration is an area of considerable current development.

4.1.3. Stray current effects

Before leaving the discussion of steel or concrete structures, the possible effects of stray d.c. or a.c. electrical currents on corrosion behaviour must be mentioned. Corrosion can occur whenever an electrical current strays from its proper conductor and finds its way through an electrolyte (sea water) to another metal surface. Most commonly, stray current corrosion is associated with d.c.; it is understood in principle but in practice it is often difficult to predict, and it is a potential problem of which designers and operators of WECs must always be acutely aware [14]. The effect of a.c. on corrosion is complicated and often insignificant, but there are instances where corrosion has been seriously enhanced by a.c. [15]. Many reported a.c. effects appear to be connected with the acceleration of corrosion already occurring, either under some form of d.c. polarization or in an already corrosive medium [16]. The transmission of a.c. electric power in WECs introduces the possibility of involving metal parts of the structure not only by resistive conducting paths but particularly by inductive coupling. There is uncertainty about the possible magnitude of stray a.c. effects on corrosion even of common engineering materials. The effect of pure a.c. on bare steel can probably be disregarded. Evidence of a.c. effects on steel reinforcement in concrete is conflicting, but an investigation already in progress for the Wave Energy Project into the corrosion of reinforced concrete in sea water indicates that effects of pure a.c. are small [17].

4.1.4. Reinforced plastics and rubber

The resistance of glass-reinforced plastics to chemical attack makes them very suitable for use in the corrosive marine environment. This is well illustrated by the amount of GRP used in the manufacture of boats and small ships. However, problems arise when these materials are considered for important structural members of cladding of WECs. There will be considerable incentive to reduce the amount of materials employed, and there is not a great deal of experience in the efficient design of GRP structures. GRP is susceptible to fatigue and also to time-dependent loss of strength due to moisture attack. For existing applications this is not too critical as adequate safety margins can be employed. Under the economic constraints of wave energy, it may be necessary to develop better design techniques and acquire better design data. Work has been initiated by the Department of Industry and the SRC within the last few years to develop design techniques and standards for GRP structures, which could be of considerable use to the wave energy programme. If GRP is to find a use as a main structural material there will be a requirement for testing, particularly for long-term static loading and fatigue cycling in sea water. Applications for reinforced plastics based on more expensive fibres such as Kevlar 49 or carbon, or hybrid composites based on combinations of glass, carbon and Kevlar 49 have not yet been seriously considered.

A partitioned flexible bag will form part of the main structure of the Lancaster device. The reliability of joints, deterioration or debonding of the reinforcement and the effects of sea water or degradation of the material will need to be established.

4.2. Mooring systems

The mooring of floating WECs at an economical cost presents a difficult problem. The devices will be subjected to particularly arduous conditions and will be expected to maintain station during severe storm conditions. A similar requirement exists for off-shore oil rigs but there high mooring costs are less unacceptable than for wave energy and that experience may not be directly applicable. The cost of establishing an anchoring point and deploying, and subsequently replacing, a mooring line is very high. Consequently, the wave energy mooring designer is confronted with the task of minimizing the number of mooring lines while maintaining an acceptably low rate of failure. In order to achieve this the wave energy device teams are currently seeking very compliant mooring systems. Under a given set of sea conditions, a floating body is subjected to a steady force on to which is superimposed a slowly varying force, with a frequency which is only a fraction of the wave frequency, and a rapidly varying force at the wave frequency. As a result of the forces and consequent displacement of the floating body, the rode (mooring line) experiences a steady, or mooring, force on to which are superimposed varying forces leading to peak forces which can be considerably greater than the mooring force and varying in frequency up to the wave frequency. The ratio between the peak force and the mooring force depends on the stiffness of the mooring system, the stiffer the system the greater the ratio. Typical estimates of mooring forces on WECs in severe seas for relatively incompliant systems are of the order of 5 tonne m^{-1} of wavefront with excursions to peak forces of the order of 100 tonne m^{-1}. There is thus considerable incentive to develop compliant mooring systems.

There are four generic rode types in current use. In order of increasing compliance these are: steel chains, steel wire ropes, parallel filament man-made fibre ropes, and plaited or braided fibre ropes. Compliance can be achieved with intrinsically stiff mooring materials, such as chains or steel wire ropes, by using the weight of the rode to form a catenary or by the use of buoys and submerged weights. All four types are being considered for the wave energy programme but, because of the novel features of mooring a WEC, it has been argued that a completely new approach to obtaining high compliance should be researched, such as the use of rubber rodes.

The immediate requirement is for sufficient information on which to base the choice of a mooring system for a prototype wave energy device, which may be launched in the mid 1980s. There is also the longer term requirement to optimize the mooring system for an array of devices. The final choice of a rode will be determined by its cost, availability, energy absorbing capability, handleability, ease and efficiency of attachment, and lifetime in use – the latter being determined by the factors listed in Table VI.

The most important life-limiting factor for man-made fibre ropes is probably fatigue cycling. Abrasive wear and damage tolerance are also important but their effects can be minimized by designing the mooring system so that the ropes are protected from rubbing. For steel wire ropes corrosion fatigue may be life-limiting whereas for steel chains interlink abrasion and corrosion will

TABLE VI Factors controlling the life of a mooring rope or chain

Effects of prolonged steady forces	
Effects of snatch forces	
Fatigue cycling	
Environmental attack:	corrosion including stress, corrosion and corrosion fatigue fishbite and marine animal attack, ultraviolet degradation
Abrasive wear	
Damage tolerance	

dominate. There is very little quantitative information available about these, and current designs of mooring systems rely on practical experience which may be insufficient for the novel features of mooring WECs.

4.2.1. Man-made fibre ropes

There are three main types of man-made fibre rope (mmfr) of interest to the wave energy programme. Two are woven ropes, of double-braided and eight-strand plaited construction shown in Fig. 7, their lay-up producing compliances and strains to failure which are much greater than those of the fibres from which they are made. The third type consists of parallel bundles of filaments contained in a tough, durable plastic sheath and exhibits load–displacement behaviour similar to that of the constituent filaments. All are manufactured from a range of materials: commonly the woven ropes from nylon, polyester (polyethylene terephthalate), and polypropylene; and the parallel filament ropes from polyester and aramid fibres (Kevlar 29). The ways in which the choice of rope construction and material affect the short-term mechanical proper-

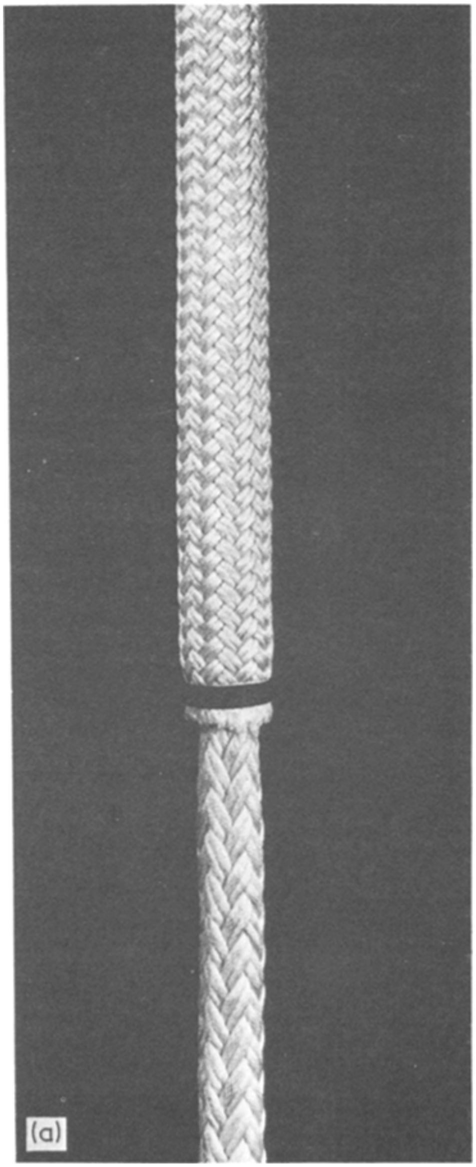


Figure 7 Man-made fibre ropes (a) double-braided, and (b) eight-strand plaited (courtesy of Bridon Fibres and Plastics Ltd).

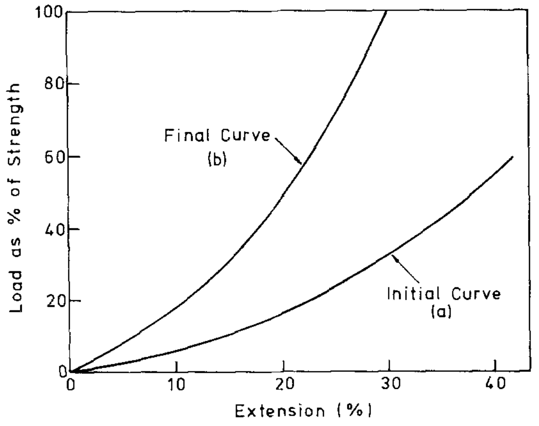


Figure 8 Load extension curves of eight-strand plaited nylon ropes (a) initially, and (b) after 120 cycles at 10 to 50% of normal breaking load [18].

ties of a rope are well understood [18–22] but there is remarkably little hard information on long-term performance in a marine environment. For similar initial rope diameters the double-braided rope is about 30% stronger than the eight-strand rope but has a final elongation to failure which is a good deal less at ~ 15% for nylon double-braided as opposed to ~ 30% for nylon eight-strand plaited [18]. "Final" elongation to failure is quoted above because the load–extension characteristics of a woven rope vary markedly during use. The initial extensibility is much greater but decreases as the rope length increases permanently and the fibres settle-in. Fig. 8, for example, shows the load–extension curves of an eight-strand plaited nylon rope both initially and after 120 cycles at 10 to 50% nominal breaking load [18]. Load cycling produces a tighter, less compliant structure, which should be allowed for in mooring design. The properties of parallel filament ropes reflect the properties of the fibres more closely. Their load–extension curves are much more nearly linear, the strains to failure are a good deal lower, and size for size they are stronger than woven ropes. Compared with woven ropes their properties change very little on load cycling as settling-in of the filaments produces a much smaller effect. For comparison the strengths, elongation to failure, diameter and dry weight in air of the maximum size ropes readily available from UK companies are shown in Table VII. In practice, it is usual to splice two woven ropes together to form a long loop running through thimbles (used for anchorage) at each end so that a mooring line made from these has double the strength quoted in Table VII. Larger parallel filament ropes have been produced for special applications.

TABLE VII Properties of the largest commercially available man-made fibre ropes

	Double-braided nylon	Eight-strand plaited nylon	Parallel filament polyester
Strength (tonne)	1720	620	200
Final elongation to failure (%)	15	30	5
Diameter (mm)	288	194	90
Dry weight in air (kg m^{-1})	55	24	5.6

There is very little precise information available about the performance of these different types of rope in fatigue. Some data have been generated by the rope companies and their customers which have shown, as would be expected, that fatigue behaviour is affected by rope material and construction. In particular, fatigue performance of the parallel filament ropes is considerably better than that of the woven rope because there is less inter-fibre wear. Tensile fatigue of woven ropes is quite severe as shown by Fig. 9 which shows data acquired from a polypropylene eight-strand plaited rope [23]. From very limited tests on tensile fatigue of woven ropes it appears that polyester is better than polypropylene which in turn is better than nylon. It has been reported that, during fatigue of nylon ropes, powder is generated at the rope surface due to inter-strand abrasion; a similar but lesser effect occurs with polypropylene, but with polyester little or no powder is seen. These observations are very tentative and have to be balanced against the fact that for a given rope construction nylon produces the strongest ropes, followed by polyester and polypropylene.

Because of uncertainties about the relative fatigue behaviour of man-made fibre ropes, the Department of Energy Wave Energy Project has initiated a research programme at the National Engineering Laboratory to obtain comparative data on ropes up to about 100 tonne breaking load. Ropes of all three constructions in a variety of materials are being tested under wet conditions to obtain S–N data. This is a useful development in understanding rope performance but much more work needs to be done. Basically there is no adequate understanding of the mechanisms of rope fatigue failure. For parallel filament fibre ropes it may be similar to that of the fibres themselves (although this has not yet been proven). For

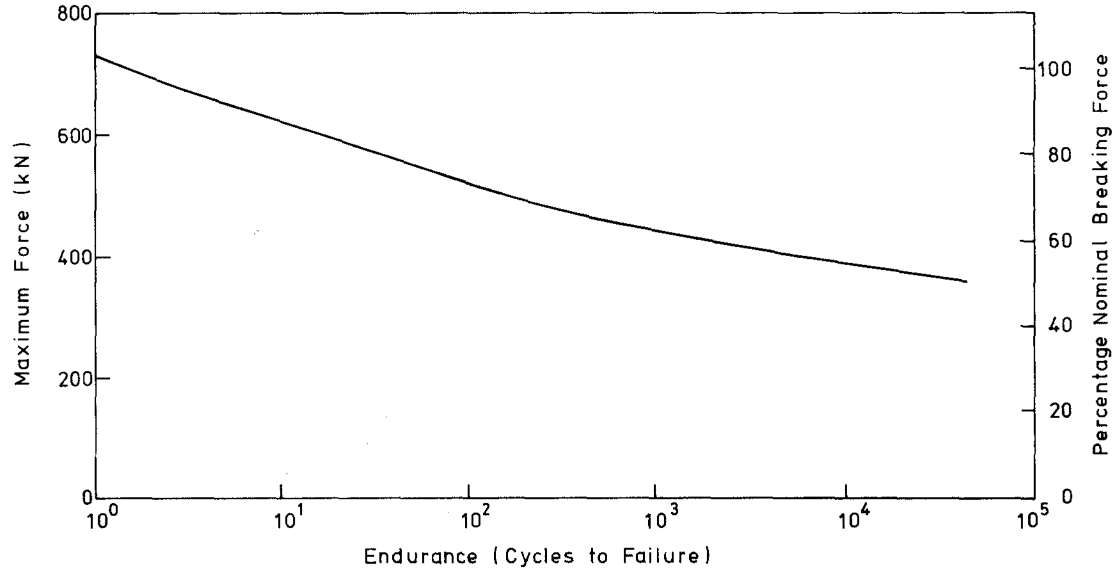


Figure 9 Tensile fatigue data for polypropylene eight strand plaited rope [23].

plaited and braided ropes failure appears to occur as a result of inter-strand abrasion but the influences of rope construction, material and environment are not properly understood. From the point of view of reliability assessment it is important to know whether Miner's Law and Goodman's Law [24] are applicable or what other predictive rules may be employed to determine in-service lifetimes.

Tensile fatigue, although thought to be the most important area of uncertainty, is not the only factor which needs further assessment. The long-term durability of fibre ropes in sea water may be affected by attack by fouling organisms or fish, or by chemical processes such as hydrolysis or ultraviolet degradation. Fishbite is known to be a problem with deep water buoys but mainly on ropes of less than 10 mm diameter. The only certain way of assessing this is by sea trials on ropes in the probable location of the devices. Creep and associated changes in strength or modulus under long-term loading at high loads may be important. Flexing fatigue or abrasion, when ropes pass over pulleys or fairleads and are severly bent, are particularly likely to degrade strength. Ropes should not be used under these conditions, but if this is unavoidable life-testing under these conditions will be required.

4.2.2. Steel wire ropes

Steel wire ropes are manufactured with a variety of constructions suitable for the very different applications for which they are employed. General information about the use and behaviour of steel wire ropes in marine applications is given by several authors [18, 19, 21] and the properties and handleability of large ropes have been documented by British Ropes [25, 26], who have recently manufactured lengths of rope with breaking strengths of up to almost 2000 tonne, the largest steel wire ropes currently available. The two ropes of most interest for the mooring of large structures are six-strand rope and spiral strand rope some of whose properties are given in Table VIII.

More information exists about the fatigue of steel wire ropes than fibre ropes, but most of the data have been obtained by dry tests on uncorroded ropes of relatively small size and at high frequency. Figs. 10 and 11 show tensile fatigue data obtained in tests on relatively small ropes [25]. These were obtained from high-frequency testing at 4.2 Hz on dry, uncorroded ropes of ~ 200 tonne breaking load. The curves have been compiled from data obtained by cycling with a super-

TABLE VIII Properties of the largest steel wire ropes currently available

	Six-strand	Spiral strand
Maximum strength (tonne)	1825	1360
Diameter (mm)	178	127
Weight in air (kg m^{-1})	130	80
Elastic modulus (GPa)	90	150
Strain to failure (%)	2.15	1.30

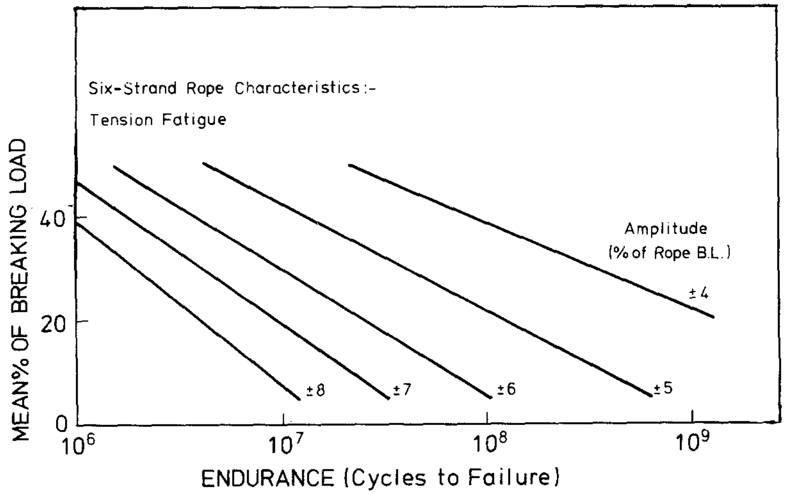


Figure 10 Tensile fatigue data on six-strand ropes.

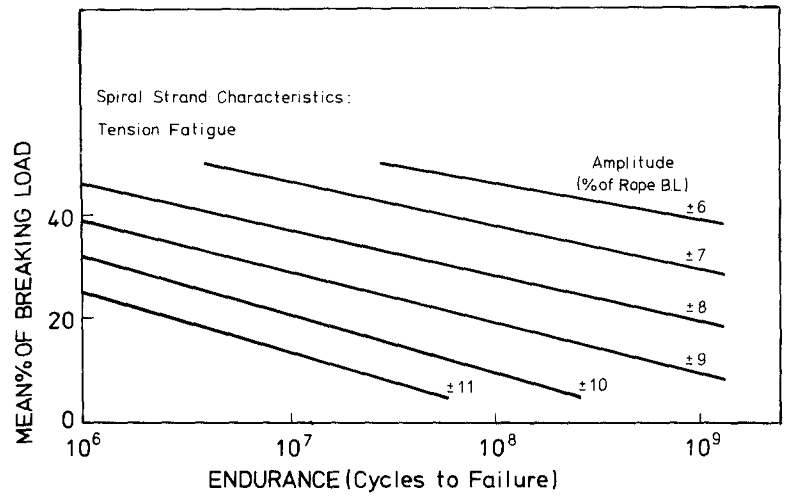


Figure 11 Tensile fatigue data on spiral strand ropes.

imposed tensile amplitude on top of a mean tensile stress. They are idealized, in that they have been obtained by fitting best straight lines to scattered data and by employing a Goodman treatment to interpolate or extrapolate into regions where data were not available.

From these data, it can be concluded that load amplitude has a much greater influence upon fatigue life than does the level of mean load. British Ropes suggest a lifetime of 2.5×10^7 cycles as representative of a 10 year working life and that for such a life the stressing should be limited to:

	Maximum acceptable mean load (%)	Maximum acceptable amplitude (%)
Six-strand	20	± 6
Spiral strand	20	± 9

where the maximum acceptable amplitude is superimposed on the maximum acceptable mean load. Figs. 10 and 11 can, however, be used to calculate other mean and fluctuating load levels for a given life and set of mooring forces. Bending fatigue of the type that would be experienced by ropes running over pulleys is far more severe, the fatigue life being strongly influenced by the relationship between the bending diameter and the size of wire in the rope [25]. The validity of the above values must be judged against the fact that the mechanism of fatigue failure of ropes is not well understood. It is likely that fretting and wear play a significant role as well as direct fatigue of individual strands. Failure occurs slowly with the strands breaking individually along the rope. In studies of the fatigue characteristics of ropes used in lifting slings, scanning electron microscopy showed clear evidence of fatigue crack growth in individual wires [27]. It has also been shown that periodic overloads can increase fatigue life even in sea water [27]. It is sometimes claimed that the gradual mode of failure of a rope, through the outer wires breaking first, enables the remaining life of a rope to be assessed qualitatively by visual examination. However, cases are known where most of the breaks occurred in the centre strands. This makes visual inspection a dubious technique for predicting remaining lifetime, and there is a clear need for good, easy NDT methods for wire ropes at sea. There is no documented, long-term experience of fatigue life of steel wire ropes of relevance to wave energy. Performance in mining, although well documented, applies only to ropes at very low static loads with mainly bending fatigue stresses. Typical lifetimes of 2×10^5 cycles emphasize the importance of eliminating any significant bending from moorings. Wire ropes in bridges are known to achieve very long life (50 years +) at moderately high mean stress levels (up to 35% breaking load) but with extremely small amplitude fluctuations. Until recently, long-term service of wire ropes in sea water was defined as longer than 1 to 2 years [26], although failures in service frequently resulted from impact loading, kinking etc. In the last 8 to 10 years large steel ropes have survived longer periods in marine conditions. For example, a $3\frac{1}{2}$ in. diameter anchor line was discarded after 8 years service as part of the mooring system of a semi-submersible rig operating in the North Sea. However, insufficient is known of the service history of these ropes or the spectrum of stresses they have received to draw firm conclusions.

Steel ropes are normally protected from corrosion by zinc coating on the individual wires with additional protection from a "blocking" material impregnating the completed rope. The protection afforded by zinc coatings will obviously depend on the corrosive environment, but a life of 1 to 2 years is typical in marine conditions for a 0.001 in. zinc layer (Table IX).

The individual wires in steel ropes are normally protected by approximately 0.002 in. zinc which would give longer lives. Experience shows that, after 10 years marine exposure, the outer wires of a galvanized wire rope are severely corroded but that the amount of remaining zinc increases further into the rope structure with the inner wires retaining their galvanizing intact.

The decrease in rope tensile strength under these conditions is relatively small, being proportional to the number of wires severely attacked. In practice it is possible to provide additional protection by plastic sheathing although this might be susceptible to mechanical damage and corrosion of the cable would occur at any breaks in the sheathing. Cathodic protection is rarely attempted since anodes have to be attached at frequent intervals along the rope, and it is difficult to obtain a satisfactory electrical bond to all the wires. Continuous sacrificial elements might be incorporated into the rope during manufacture, but this has yet to be evaluated in service. The use of impressed current cathodic protection with remote anodes operating at higher voltages is probably ruled out because of the danger of "over-protection" causing hydrogen embrittlement of the steel.

Although a good deal is known about the separate effects of fatigue and corrosion, little is known about their combined effects in corrosion fatigue, as discussed in Section 3. Fig. 12 shows the corrosion fatigue of a bright steel cable wire in sea water [5]. This test was carried out at high frequency (100 Hz) but the effect of the corrosive environment was apparent even at the highest cycle stresses, when the specimens failed within the first hour. Such a dramatic reduction in fatigue life is believed to be primarily associated with the effect of corrosion on fatigue crack initiation and Fig. 13 shows that small diameter, bright steel wire ropes that had been immersed in the sea at a constant 30% breaking load for periods of time up to 12 weeks showed a definite correlation between corrosion damage and fatigue [29]. Fig. 12 shows that cathodic protection, by eliminating corrosion, restored the fatigue strength of a steel wire in sea water, and galvanizing might be expected to produce similar results on new wire ropes tested at high frequency in sea water. However, in service,

TABLE IX Life of zinc coatings on steel wire rope in marine environments [28]

Thickness ($\times 10^{-3}$ in.)	Life* (months)			
	Quiet sea water	Sea water 2 ft sec^{-1}	Splash zone	"Sulphide" mud
0.3–0.5	12	6	12	12
0.5–1.0	24	12	18	24

*Time to initiation of significant corrosion of underlying steel.

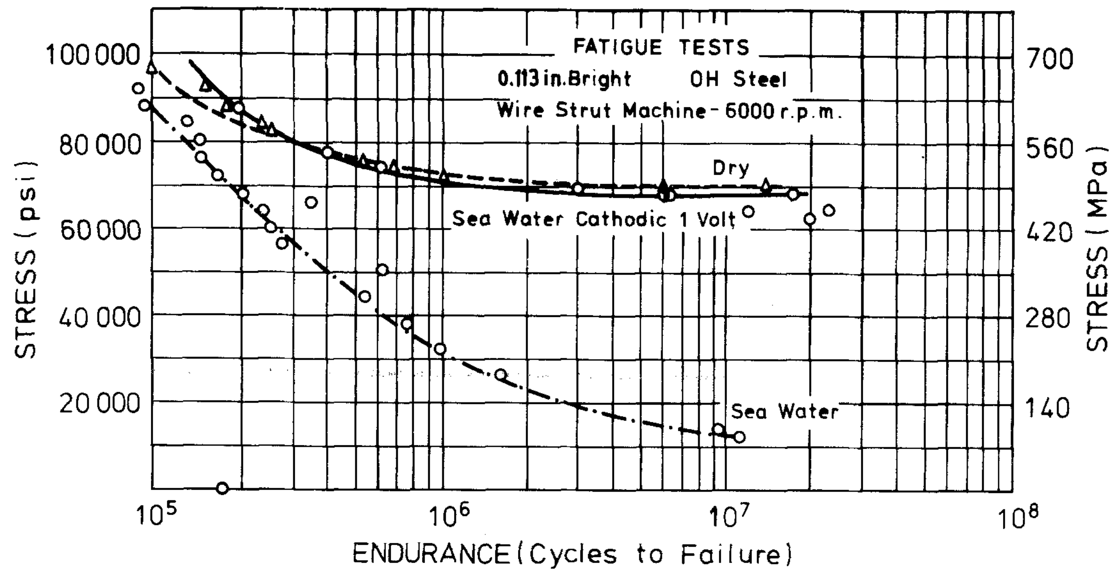


Figure 12 Corrosion fatigue of steel cable wire in sea water [5].

perhaps over a period of several years, the zinc coating will be lost and the individual wires will be exposed to the full effects of corrosion fatigue, at frequencies typical of wave motion where crack growth rates are high. A further possible complication may arise even when sufficient zinc remains to protect a wire from corrosion since, although it may eliminate the effect of corrosion on crack initiation, cathodic protection does not necessarily reduce the rate of growth of a fatigue crack once it has formed [7].

In current applications there is no evidence to

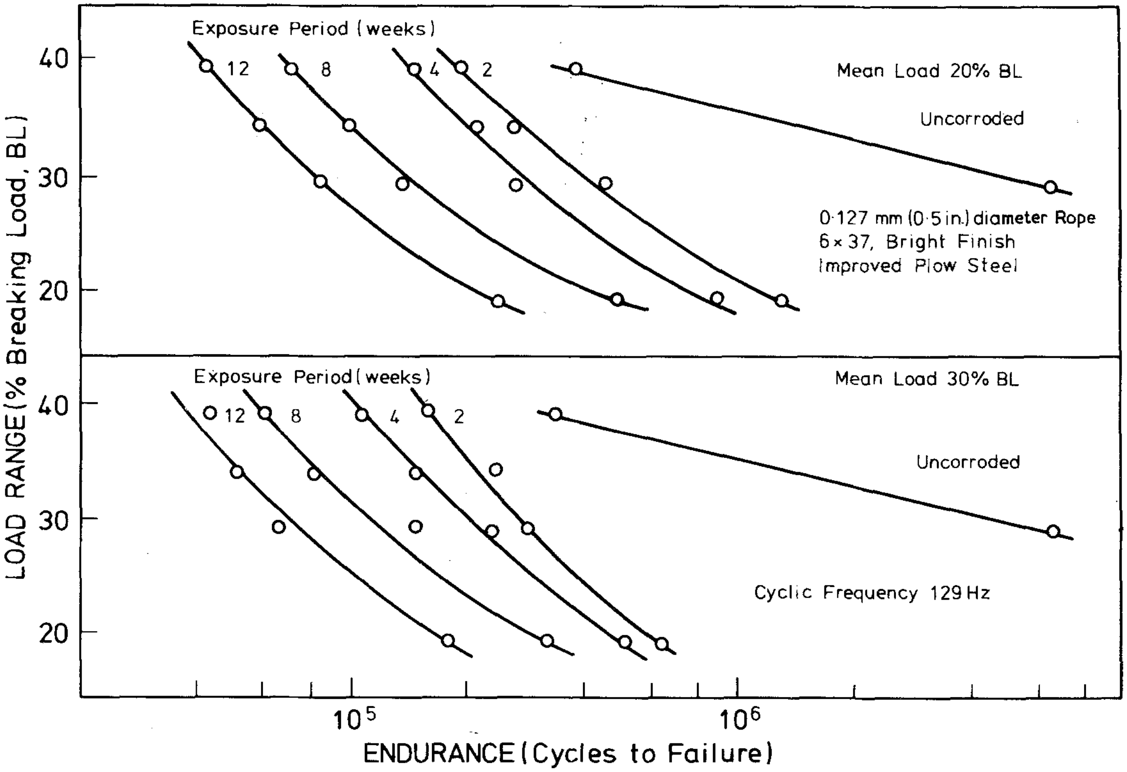


Figure 13 Effect of prior exposure in sea water and mean stress on fatigue performance of wire rope in synthetic sea water [5].

suggest that corrosion fatigue is the present life limiting factor of large ropes. It may be that present methods of inhibiting corrosion may satisfactorily protect large ropes in wave energy applications. However, if there is a significant effect of sea water corrosion on the long-term behaviour of ropes fatigued at wave frequencies, it could profoundly influence estimates of the cost of a wire rope mooring system, and data are urgently required to test the validity of existing predictions of life based on dry fatigue data. For that reason the Department of Energy has recently initiated a collaborative programme of research at NEL and Harwell to determine the significance of corrosion fatigue in steel wire ropes.

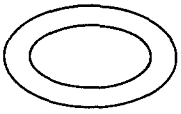
4.2.3. Chains

There are three factors likely to limit the lives of chains: interlink abrasion, corrosion and weld cracking.

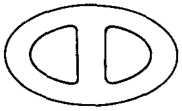
If links rotate with respect to one another considerable wear occurs and, in some locations (notably off South Africa and in the Mediterranean), chains need to be replaced at 6 monthly intervals. If the system is arranged so that interlink abrasion is minimized, considerably longer lives are feasible and Lloyds Register suggest that a 10 year life may be achievable with the limitation that the maximum load should not exceed 70% of the proof load and therefore that the mean load should be limited to 20 to 30% of the proof load. Presently there are two main types of chain: open link and stud link as illustrated in Fig. 14. Stud link chains are less prone to tangling and are stronger than open link chains. Because ease of storage and flexibility are not as important for wave energy application as for conventional applications, totally different constructions could be considered for the wave energy programme. In order to reduce the wear problem it might be better to design a chain based on a "link" design as shown in Fig. 14, where the longer length of each link reduces the number of wearing points and perhaps a superior bearing surface could be incorporated as shown.

Galvanizing and cathodic protection tend to be of little use for chains because the galvanized layer rapidly wears away and cathodic protection is not feasible because it is not possible to maintain good electrical contract between the links.

The quality of chains is currently rather variable. Frequently the links contain weld cracks or cracks in the bent metal. Lloyds Register quote the case of one 4 km length of chain in which 90% of the links contained cracks. It is not usual practice to carry out NDT examination of chains prior to, or during, use. If chains are employed for mooring WECs, however, it may be advantageous to establish NDT as routine for examining for cracks in links.



(a) Open Link



(b) Stud Link

(c) Improved Design

Figure 14 Types of chain link.

Fatigue tends not to be a problem with chains in marine usage because under normal sea conditions they are employed at relatively low loads. However, higher loads may be necessary in the wave energy programme moving failure of chains into a different regime. Presently chains mainly fail under snatch-loads, and the failure rate of chains in marine use in the UK and USA is low at ~ 0.5% per year.

4.2.4. Rubber rodes

Because of the need to reduce the forces in mooring ropes by increasing the compliance of the mooring system, it has been suggested that consideration should be given to the use of rubber rodes. These might be monolithic rubber bands, woven rubber ropes, rubber ropes of parallel fibre construction, or something as yet unspecified. Table X compares the strength and strain to failure

TABLE X Typical tensile properties of bulk rubber, rubber filaments and non-elastomeric fibres

	Strength (MPa)	Strain to failure (%)
Rubber (bulk)	30	600
Rubber filaments	50–90	600
Man-made fibres	600	20

of rubber filaments, bulk rubber and typical synthetic non-elastomeric fibres.

Rubber rodes could certainly absorb considerably more energy even than man-made fibre ropes, but compared size for size (in the unstressed state) would be considerably weaker. Some rubbers are known to have good fatigue properties and tear resistance, and this could be an advantage in their use. It is possible, however, that too great a compliance may be unacceptable because of necessary restrictions in the movement of the devices such as may be imposed by problems of fatigue of power take-off cables, or inter-device collision. Some development of prototype novel mooring lines based on rubbers is currently under way.

4.2.5. End fittings

The conventional method of permanently fixing a plaited or braided fibre rope is by forming a loop, perhaps to enclose a thimble, and splicing the end of the rope back into itself. A well-made splice generally reduces the tensile strength of a rope by not more than 10%. In laboratory fatigue testing of ropes, however, fatigue failures often begin at the splice and such data should be regarded as fatigue data of spliced end loops rather than of undisturbed ropes. It has been argued that this is the most realistic data to obtain because this is the normal method of end-fixing. This is an oversimplification because, if such end-fittings drastically reduce fatigue lives, there will be considerable impetus to develop improved methods. Further, it cannot be concluded that, because static strength is reduced by only 10% on splicing, the effect on fatigue will be as low.

Parallel fibre ropes are usually terminated with steel or aluminium end-fittings which utilize a tapered spike wedge to lock the load-bearing fibre core in a tapered socket by means of frictional forces. In the limited amount of laboratory fatigue testing of these ropes carried out to date, failures have always occurred at the end-fitting, either by failures of the shackle pin or by fretting failure of the peripheral fibres as they enter the end-fitting. There appears to be a need, therefore, for development of better end-fittings.

Steel wire ropes are traditionally spliced but a preferred method for this application is termination by insertion into a socket in the termination into which is cast zinc or resin. The rope industry has carried out development of end-fittings which are less fatigue-sensitive than the rope itself, and developments are foreseen with large ropes cast into filled polyester resins or concrete, which are more likely to be successful for long-term sea water immersion.

4.3. Primary power take-off systems

The form of primary power take-off for four of the devices (i.e. the OWC, Rectifier, Vickers device and the Lancaster flexible bag) is dictated by their mode of operation, since in essence the device itself is a cyclic low-pressure hydraulic system. Power take-off is simply the appropriate turbine; either a low-head water turbine for the Rectifier and Vickers device or an air turbine driven by air displaced by water for the OWC and Lancaster device. The Duck and Raft systems both rely on relative motion of two parts of the structure, and therefore have greater freedom of choice in designing their power take-off. In principle this could be entirely mechanical and rack and gear systems have been used in the $\frac{1}{10}$scale trials of both devices. Scale up of a mechanical system will certainly introduce new materials requirements, but so far both device teams have favoured a hydraulic system which allows them to transport power and gives flexibility in electrical generator design. The hydraulic systems considered range from high-pressure oil to low-pressure sea water, and each has its advantages and disadvantages; a high-pressure oil system is relatively compact but presents a pollution/fire hazard, whereas a low-pressure water system is relatively safe but must employ very large diameter pipe-work etc. Sea water hydraulics has the particular advantage that surplus energy can be readily dissipated and the system can be cooled simply by exchange with the surrounding sea.

4.3.1. High-pressure oil systems

The feasibility of long-term maintenance-free running of high-pressure oil systems is a matter of concern. For example, tests at the NCB Research Establishment at Bretby [30] have shown that very few hydraulic pump units last their standard 1000 h test schedule, which hardly augers well for WECs. Usually breakdown occurs at the seals, which are an obvious area for development. In general, mineral oil hydraulic fluids do not have a corrosion problem under correct operating conditions, although an oil hydraulic system will introduce a potential corrosion problem in the form of an oil–sea water heat exchanger, and a high integrity exchanger is likely to be an expensive component. However, water is sometimes added to hydraulic oils to reduce the fire hazard, or the oil may be accidentally contaminated. Microbiological deterioration can be a problem in these water-in-oil emulsions [31] leading to corrosion, excessive wear and filter blockage. Research by Shell Laboratories [32] using vane-type pumps has shown that wear particles show less tendency to settle in this type of fluid. Wear appears to predominate in industrial practice, and analysis of fluid from many systems has shown that more than 90% of the solids are magnetic and less than 1 μm in size.

4.3.2. High-pressure sea water systems

Operating a sea water system at high pressure will minimize its volume at the expense of high flow rates and the need for materials to withstand impingement and erosion/corrosion. Since a sea water hydraulic system will be free to exchange when necessary with the surrounding sea water, care will be needed to ensure that ingestion of sand or air does not accelerate corrosion/erosion processes. Typically a system operating at 7 MPa might require flow rates of 10 m sec^{-1} in pipes 0.25 m diameter. There is no relevant experience, but it is likely that the problem of seal wear, that has proved so difficult to overcome in oil systems, will be eqully detrimental to long-term maintenance-free operation of high pressure sea water hydraulic power systems. There is a considerable body of experience of alloys for ship sea water cooling systems, fire hydrants, etc. and it is apparent that, although much can be done in design to minimize corrosion, the choice of alloys will be limited. Plastics are now being used in sea water systems, but there is little long-term practical experience.

Metals such as carbon steel and cast iron corrode in sea water at a high rate which increases with flow rate [5] and are unsuitable for high reliability systems, although the "Ni-Resist" austenitic cast irons may be used for massive components such as pump or valve bodies. Austenitic stainless steels are unaffected by velocity, but tend to pit in quiescent sea water, and are susceptible to crevice corrosion. They are widely used for pump bodies and impellers, and are frequently cathodically protected, using mild steel sacrificial anodes, to prevent crevice corrosion. Vulnerable surfaces may also be overlaid with an alloy such as Inconel 625 which is more resistant to crevice corrosion that the austenitic stainless steels.

Copper-base alloys are widely used in sea water systems, but all exhibit a critical velocity above which impingement attack (intense localized pitting) occurs. This critical velocity increases for the more highly alloyed materials (Fig. 15) [6]. Nickel aluminium bronze or manganese aluminium bronze castings are favoured for pump components, combining strength with resistance to corrosion by flowing sea water.

If a system contains several different alloys, galvanic coupling can affect corrosion. The galvanic series (Fig. 5) gives the potential of a number of alloys in flowing seawater, indicating which of the metals is anodic and will therefore suffer corrosion if they are coupled together. Sometimes galvanic coupling can be helpful as in the sacrificial protection of stainless steel by mild steel, but it is generally unwise to couple a small area of an anodic metal to a large cathode. A recent useful

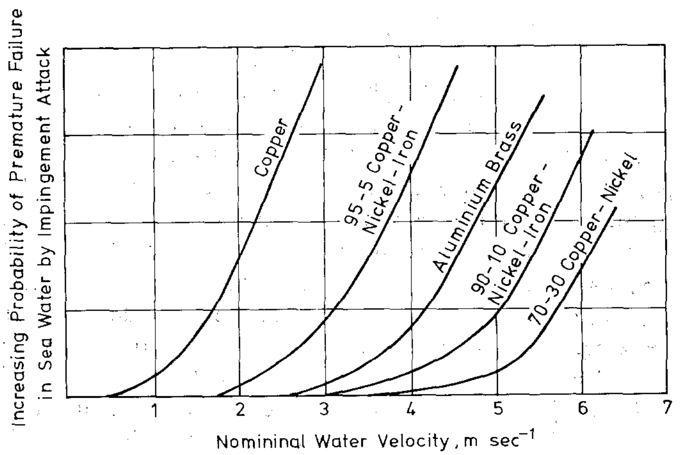


Figure 15 The increasing probability of impingement attack on tube alloys with increase in sea water velocity [6].

guide to designers has been provided [33] in the form of data and equations to calculate current flow in bimetallic couples with different area ratios.

There is still little practical experience of plastic pipes and fittings in ship's sea water systems because of the greater risk to cooling supplies to machinery, etc., in the event of fire or mechanical damage. The use of plastics in a high-pressure hydraulic system would avoid many corrosion/erosion problems, and this seems a likely area for development.

4.3.3. Low-pressure sea water systems

Low-pressure sea water systems present a simpler corrosion problem than an equivalent high-pressure system. Their very large size rules out the use of any but the cheapest materials available, but low water velocity removes the need for more costly highly alloyed materials, except perhaps for pump components and turbines. A typical enclosed system might carry $10\,m^3\,sec^{-1}$ sea water at 0.35 MPa, $2\,m\,sec^{-1}$ in 2.5 m diameter pipes, and such a system could be fabricated almost entirely from cast iron and steel and protected against corrosion. Comparable systems are in use at sea water-cooled power stations, where experience of protection by coatings is not particularly good, but CEGB experience at Fawley Power Station [34] indicates that with careful design, an impressed current cathodic protection system can prevent corrosion in uncoated steel sea water intake pipes, pumps and valves. Similarly a cathodic protection system has proved fully effective against corrosion of turbine blades in the La Rance tidal power plant [35].

Protection currents increase with flow rate, and CEGB find current densities of $\simeq 100\,mA\,m^{-2}$ sufficient at a nominal $2\,m\,sec^{-1}$ flow compared with the 20 to $30\,mA\,m^{-2}$ commonly required in quiet sea water. It must be noted that the success of impressed current systems on WECs will require improved long-term reliability, particularly of control equipment, but this should be well within the capability of existing technology.

Low-pressure sea water systems offer particularly good prospects for introducing non-metals both as main structural material and for components. GRP is already finding use in power station cooling circuits, and prices for complex shapes in GRP are competitive with mild steel [34]. A need to produce special pumps, particularly if low-frequency large volume pumps are used for the Raft device may offer the opportunity to produce an all plastic system free from the constraints imposed by existing designs.

As with other systems, long-term reliability of seals and bearings are still in question, although maintenance periods may be considerably extended. For example, the La Rance turbines operate satisfactorily at present with annual renewal of oil in all runner hubs carried out as a precautionary measure [35].

4.3.4. Air turbines

These turbines encounter the particularly severe corrosion conditions found at the splash zone and atmosphere immediately above the sea, and the sometimes warm humid salt-laden air operating the turbine within an OWC or Flexible Bag may be even more corrosive than the normal marine atmosphere. The possible effect of condensation droplets or splashes of water in rough conditions impinging on turbine blades at high velocity must also be considered. Compared to the systems with bearings immersed in sea water or seals subjected to high pressures the air turbines seem generally likely to have less severe maintenance problems. The austenitic stainless steels and higher nickel alloys appear particularly suitable for air turbine components, and some copper alloys may also be suitable. However, plastic fabrications such as GRP, which are light, strong and completely avoid corrosion problems are likely to offer considerable advantages in air turbines, although their resistance to impingement has yet to be determined.

4.3.5. Bearings and seals

The problems of bearings and seals in WECs have not yet been ivestigated in any depth. There is wide experience of bearings and seals in hydraulic equipment, pump systems, etc. Regular maintenance is usually accepted, and it may well be difficult to achieve reliability with existing designs and materials without encountering unacceptably frequent maintenance. No doubt improvements could be made to improve long term maintenance-free operation, but research and development will be needed to achieve reliability for WEC applications.

The very high load oscillating bearings required for the raft design of WECs are outside existing experience. They will need to be considerably larger than equivalent continuous rotation bearings. Water lubricated plastic shell bearings may be feasible if sufficiently low friction coefficient and therefore low energy dissipation can be achieved. Oil- or grease-filled bearings are more likely, and sealed roller bearings could be much smaller, but these rely on sealing to retain the lubricant and excluded sea water, a problem that has not yet been completely overcome in other applications.

4.3.6. Power cables

On present designs of wave energy "power stations" there is a need to deploy flexible power cables between devices and transformer/converter stations. The limit for flexible elastomeric cables is about 33 kV a.c. and if loads in excess of 10 MW are to be transmitted a new generation of cables will have to be developed. The fatigue life of 33 kV cables in water is unknown and experiments have been started recently to remedy this [36]. The flexing fatigue behaviour of the cables and armouring will not only influence cable survival but will also limit the amount of compliance possible in the mooring systems of floating devices. The link from the transformer/converter station to shore is envisaged as conventional d.c. submarine cable and no new problems should arise here.

5. Conclusions

Important generic materials problems facing the development of Wave Energy Converters have been reviewed and gaps in existing technology identified. The largest gaps appear in areas where fatigue of components in contact with sea water is likely. The behaviour of both metal and man-made fibre mooring materials is not well known and experiments have started to remedy this. Similarly, the flexing behaviours of the necessary a.c. power cables and sheathing are largely unknown. This may well limit the compliance allowed in the mooring system which in turn determines the forces to be overcome in operation.

Most corrosion problems should be avoidable by the correct application of known technology. If this proves too costly, alternatives, such as the use of coatings on cheaper concrete, must be considered. Marine fouling introduces further complications and preliminary experiments have shown that heavy fouling is to be expected in the areas of likely WEC deployment. More work is needed on the interaction of fouling and corrosion processes in structural steel and reinforced concrete, the likely materials of WEC construction, although limited experiments are in progress. Stray current corrosion from a.c. generated on board WECs, once considered a likely problem, is not thought to be serious as a result of recent experiments. Rubbers and reinforced plastics will have several important applications in WECs and additional work on their wear and fatigue properties in sea water may be necessary.

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Received 1 October and accepted 25 October 1979.