*Trans. Nat. Acad. Science & Tech. (Phils.)*
*1988: 10: 1-32*

# WORLD PROGRESS IN WAVE ENERGY – 1988

Stephen H. Salter
*Department of Mechanical Engineering, University of Edinburgh, Scotland*

## ABSTRACT

Waves provide a source of renewable energy which can be extracted with a surprising degree of efficiency by several different types of equipment. Although the technology is new, its advocates claim that it is now competitive with electricity generation from diesel plant in remote island sites and point out that many future developments are still to be made.

The verbal presentation will explain the essential background physics of wave power devices and will include slides and film of models and full scale working prototypes, particularly the Norwegian plant which will shortly be installed in the Pacific.

The written paper will attempt a classification of the various designs in terms of their hydrodynamic interfaces, means of reaction, power-conversion mechanism and survival characteristics and is intended to inform future potential owners in the Pacific about important features.

## Introduction

The energy crises of the Seventies threatened the standard of living of the developed countries and led to vigorous research into a variety of possible replacements for fossil fuel – particularly for oil. Sea waves were one of the more novel of the renewable sources which were taken seriously. They were of interest in Scotland because of our exposed position in the North Atlantic. The supply of raw energy was quite large and was at its maximum during the winter period of maximum demand. The efficiency of small models in test tanks was very high with several different designs achieving peak values of nearly 100%. Britain gave official support for research into at least ten different ideas for converting this energy to electricity and work began in several other countries, notably in Norway Masuda in Japan had been working on it since 1945.

With an intense programme of model tests and theoretical work from brilliant mathematicians the sizes of full-scale plant were reduced and high conversion efficiencies extended to longer and longer waves. Special turbines and hydraulic machines for power conversion were invented. Data on stress and fatigue were collected. With help from civil engineers, the first tentative full-scale designs were produced and various estimates were made of electricity costs. The earliest of these estimates were all impossibly high but the trend was sharply downwards till the point was reached in 1982 when several of the British teams believed that they had achieved the targets set by the politicians. To their astonishment the British programme was wound down in 1982, as a result of some secret papers presented to a Department of Energy committee by the Energy Technology Support Unit at Harwell, the body which controls renewable energy research in Britain continued to this day and are at present the subject of a Parliamentary inquiry(1). A useful review of progress to that point was published by the manager of the British Programme(2).

Although there is much less oil and gas in the world than there was in 1973 and although British oil production has begun to decline, apathy about energy supplies has replaced the enthusiasm to support research. Britain now spends less on renewable energy research than any of the other industrialized countries – less per capita than Spain or Greece. We are forgetting the painful lessons and will have to learn them all over again.

By 1982 teams in Norway had achieved the same pattern of cost reductions as the British but were then allowed to go on to build two working prototypes at a site near Bergen. These have been followed by Norwegian sales in Pacific areas where many islands have good wave conditions. It may be that the Pacific will become the center for future wave energy systems.

## Wave Climate

Anybody who is thinking of installing a wave power device must pay great attention to the nature of the resource. The key factors are the statistical distributions of wave amplitude and wave period, but it may also be helpful to know about directions of approach, seasonal variations and duration of calms. The information can be slow and quite expensive to collect but will find uses in many other marine activities including harbor design, offshore oil exploitation and fishing. A great deal of data already exists and intelligent extrapolations can be made to extend the coverage.

There are many methods of collection. The earliest was visual observations from shipping. Although the coverage is uneven, the results agree surprisingly well with later instrumental methods. A collection of wave observations by Hogben and Lumb(3) omitted most of the Pacific, but Pacific measurements are included in a succeeding edition(4). Unfortunately, following the privatization of the National Physical Laboratory, the price of the publication was also increased from £6 to £295 putting it beyond the reach of British University research workers.

The wave community is particularly indebted to Laurie Draper and the National Institute of Oceanography – now the Institute of Oceanographic Sciences – for their extensive collection and analysis of wave data(5) (6) (7) (8) (11) (14). I believe that having wave measurements for the North Sea before anybody knew of the presence of oil and gas has saved Britain hundreds of lives, several oil platforms and and oil production worth thousands of millions of pounds. Despite this handsome return on pure research, present official policy is forcing the closure of the wave measurement research teams.

Much of the information was obtained with Tucker's shipborne wave recorder which was fitted to weather ships. This combines pressure readings from a transducer in the hull with double integrations of vertical acceleration. If a ship is not available then measurements can be made from the accelerations of a buoy, and this service is available on a commercial basis from several companies. Satisfactory wave measurements have been obtained from satellites[9] and shore-based radar[10] and I expect that these sources will play an increasing role in future. As the swell which will come tomorrow is already in the sea we should be able to rely on accurate wave energy forecasts which will be useful for planning the schedules of other generating plant.

Rough visual estimates can be made from the beach with binoculars by observing how much of a small boat is obscured when it is in a wave trough. Another useful indication of a suitable wave climate is the presence of white capped breakers in deep water when the period of the waves is 7 seconds or more. Tornkvist has published the map shown in Figure 1, which suggests that most sites exposed to the open Pacific ought to be considered, with power densities of 20 kilowatts per meter in equatorial zones rising to 80 or more in the high latitudes.

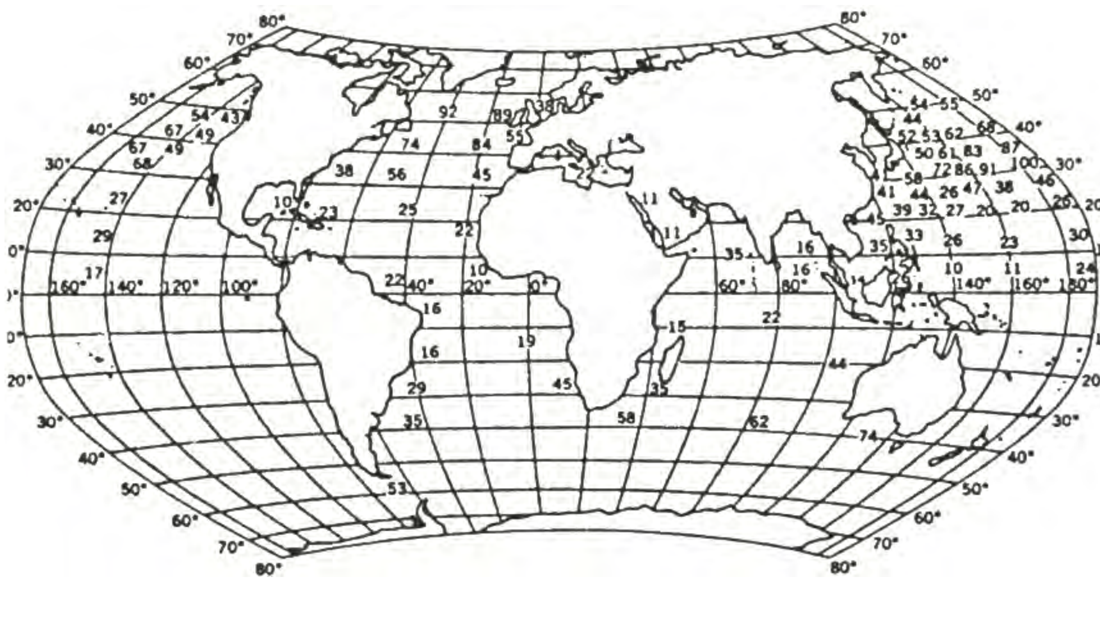


Figure 1. Estimates of the distribution of wave energy made by Tornkvist. Values are given in kilowatts per meter width of sea frontage. It is reasonable to expect that the South Pacific would be roughter than the North.

Finally, as the relationship of wave height to wind speed and duration is known(11), it is possible to produce excellent wave statistics from historic meteorological data. Denis Mollison of Heriot Watt University has written computer programs to interpret meteorological records in the form necessary for wave energy predictions and has applied these to several potential sites(12) (13). Figure 2 shows results for a good Atlantic site.

It is possible that previous predictions for the Atlantic – and for other regions which have used Atlantic data as a yardstick – may prove conservative, for reasons that I find fascinating. In a recent letter to Nature(14), Draper presents the astonishing evidence that the North Atlantic has been getting rougher. Despite the

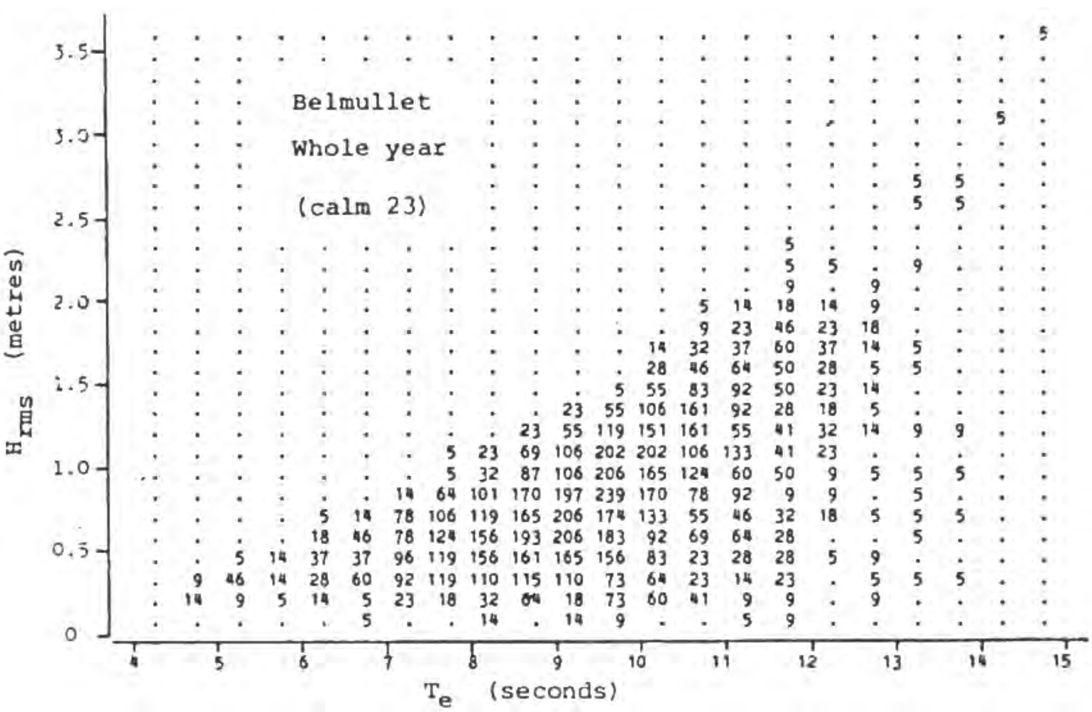


Figure 2. Mollison's interpretation of power levels for a good Irish site based on hindcast wind data from the British Meteorological Office. The table shows the probability in parts per 10,000 of getting any combination of root-mean-square wave height and energy period. Power density in kw/m for each cell can be calculated from the expression 7.9 $H^2_{rms}$ Te.

fact that the long term values of wind speed have not changed and that the instruments and calibration methods are identical, the observations from weather ships show a rise amounting at one site to 40% over the years 1962 to 1985. Most possible explanations have been excluded.

The only one that I can offer is that since the earliest measurements were taken the amount of oil spilt in the Atlantic has been reduced. The input of energy from the wind works through the shear stress between air and water. Very thin surface films can affect this transfer. Oil came partly from wrecks of shipping destroyed during World War II and also from illegal but deliberate discharges from tankers cleaning their bilges. Levels reached tens of milligrams per square meter. Analytical techniques which allowed the identification of sources of spilt oil have led to a reduction, and perhaps this is allowing a greater transfer of energy from air to water.

The values of the density of sea water and the acceleration of gravity of the MKS system of units allow a convenient rule of thumb for the energy in a regular wave train. If you square the height from trough to crest in meters and multiply by the period in seconds you get the power density in kilowatts per meter within 2%.

The statistics of wave height have been the subject of considerable study. For most engineering purposes one can assume that in a constant sea state, whether of swell or local windsea, the distribution of water positions follows a Gaussian distribution like that shown in Figure 3. There is a minor skewness towards higher crests and less low troughs which may affect calculations about overtopping, but for most purposes the Gaussian theory works very well.

This means that from knowledge of the root mean square value one can predict the chance of getting any other. It follows that, in the linear region of operation, the statistical properties of parameters like position, pressure, flow-rate, torque, force, water level and angle are also likely to follow a Gaussian distribu-

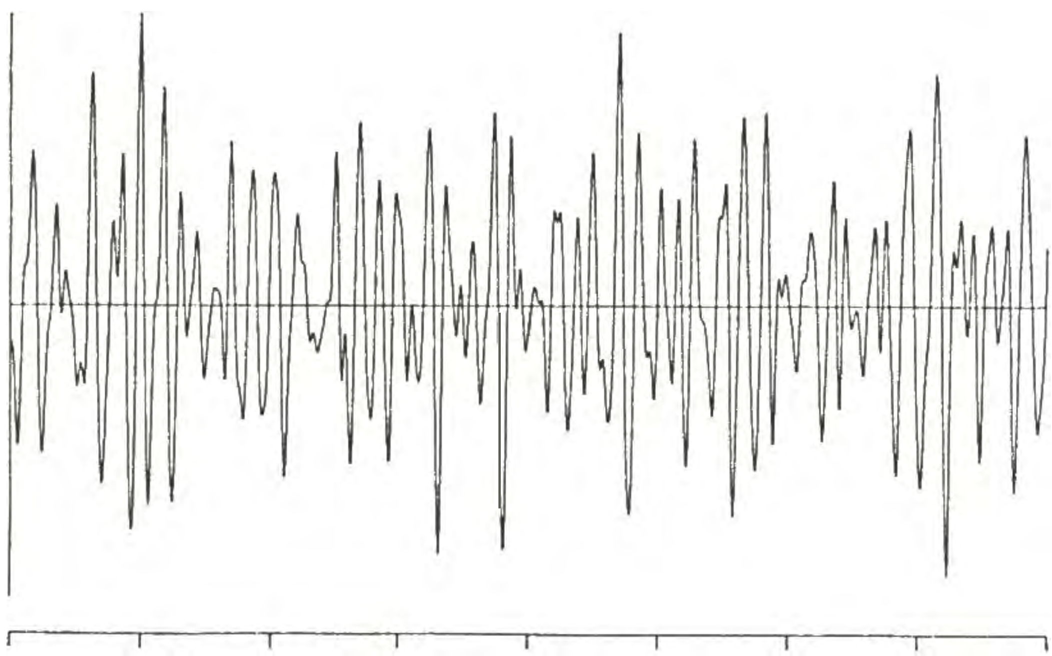

Figure 3. A typical wave record taken over 8 minutes. The Gaussian distribution can be used for nearly all engineering estimates.

tion. The wave engineer must provide enough range for all of them to take their extreme value, or else devise means of preventing them from going too far. I took it as an early axiom that there is no such thing as an end-stop in wave energy.

In deep water the attenuation of wave energy is very low. The chief loss mechanism is breaking and this does not occur when swell moves out of the area in which it has been generated. This means that many Pacific sites will be able to obtain a fairly steady energy flow from winds that have been blowing thousands of kilometers away with much less of the afternoon peak of wind energy which is often observed in island climates.

Waves are attenuated when they move into shallow water. The loss factors depend on wave period, depth and bottom roughness. The long period parts of the spectrum are affected most. Bagnold[15] has shown that sand ripples have friction coefficients which are far higher than might be expected – one hundred times that of a ship hull. Bottom friction can lose several watts per square meter in depths less than about 80 metres. This seriously reduces the energy input to inshore sites with large continental shelves such as the Hebridean wave field[16]. It should apply much less in Pacific island sites where the slope of the sea bed is usually greater.

The final effect of shallow water is refraction. The propagation velocity of waves in shallow water depends on the depth and so an uneven bottom can act like a group of optical lenses. This has the effect of producing some sites with unusually high energy and others where energy is unusually low. The Norwegian company Norwave has developed computer techniques to predict the enhancement ratios from the soundings on charts. Every wavefield so far examined has hot spots with annual energy input double – sometimes three times more than – that in the open sea. It was ironic that one of the waverider buoys deployed in shallow water off South Uist for the British wave programme should have been placed in a cold spot which reduced its measurements to one third of that in deep water while the Philips Ekofisk platforms in the North Sea should have been sited on a hotspot which was particularly affected by the prevailing wave direction.

We might have expected power input to rise with the square of wave height while structural stresses rise only with the first power. However the economic gain at hot spots can be even more because the breaking of the biggest waves limits the extreme loads. Hot-spot siting is of great importance for small islands which may get all the power they need from one or two of them. If you want a quick indication before spending money on the Norwave survey fees, your own fishermen will tell you where to look.

## Types of Devices

Just as there have been many different successful designs for aircraft and just as there have been changes in what is needed for success, there are many possible types of wave device and, I believe, more still to emerge.

It is possible to classify them in terms of:

(1) the nature of their working interface with the sea;
(2) their symmetry relative to the wave direction;
(3) the packing density of groups of devices;
(4) the means of obtaining a reaction to wave forces;
(5) the mechanism of their power conversion and the sophistication of control strategy;
(6) their mechanisms for energy storage and for the combination of output from adjacent devices;
(7) their position relative to the water, sea-bed or land;
(8) the materials from which they are constructed;
(9) the means by which they survive extreme conditions.

An understanding of these classifications provides a general view of the technology.

## Interfaces

The simplest wave devices are symmetrical with respect to the wave direction. Output can be doubled for uni-directional waves if they can be made asymmetrical so as not to transmit waves astern. Water acts on interfaces by exerting pressure. Four types of interface have been proposed. The most popular is the water-to-air junction used in devices called oscillating water columns proposed by Masuda in Japan and taken up many others. Pressure can also be transmitted to air contained in a flexible bag as first suggested by Michael French(17) at the University of Lancaster and later developed by Sea Energy Associates for their clam(18), designed at Lanchester Polytechnic in Coventry. Water pressure can be transmitted to moving, hard-skinned structures as in the raft designs of Sir Christopher Cockerell(19) in England and Glen Hagen in America(20) (21), the buoy of Budal and Falnes(22) (23) in Trondheim, the submerged cylinder of David Evans at Bristol(24) (25) and the duck developed at Edinburgh University. Finally it is possible to use an entirely static interface to redirect the pattern of water movement as in the Norwegian tapered channel device invented by Even Mehlum(26).

The popularity of the oscillating water columns is derived from their apparent simplicity and the widespread belief that simplicity is a good feature of engineering design. Masuda's scheme started as a box with its bottom open to the sea. Wave action caused water within the box to rise and all so as to exert an alternating pressure on the air above it. Air movement was then converted to electricity by turbines. There have been considerable improvements to the efficiency of oscillating water columns made by changing the shape of the underwater structure to a side opening(27) and by addition of "harbors"(28) (29). This term is a translation from a Norwegian word used by Bonke and Reitan of the Kvaerner Brug team to describe vertical side walls, built in front of the box, which induce a secondary resonance. All improvements are aimed at matching the natural resonant frequency of the water column to that of the useful part of the wave spectrum without having to use very large structures.

When the first bag devices were proposed it seemed as though their material content would be very low. One had to pay for surface area of the bag but drew benefit from the volume that it enclosed. Ballast was necessary to sink the bags against Archimedes forces but this ballast could be provided as a fairly cheap concrete structure. Figure 4 shows the double-sided design of Michael French and Figure 5 the single-sides SEA Clam.

It would be wrong to think of these bags as fragile children's balloons. They would be made of material much more like the fabric of motor tires but would not suffer the heat which is the worst stress for tires. A feature of the bags is that turbines can be kept in relatively dry conditions away from the salt spray suffered by the exposed turbines in oscillating water columns.

Designers of bag devices are irritated by the necessity of finding a place for their air to go. The pressure changes associated with average sized waves are much smaller than atmospheric pressure and so, to first order, air can be treated as in-

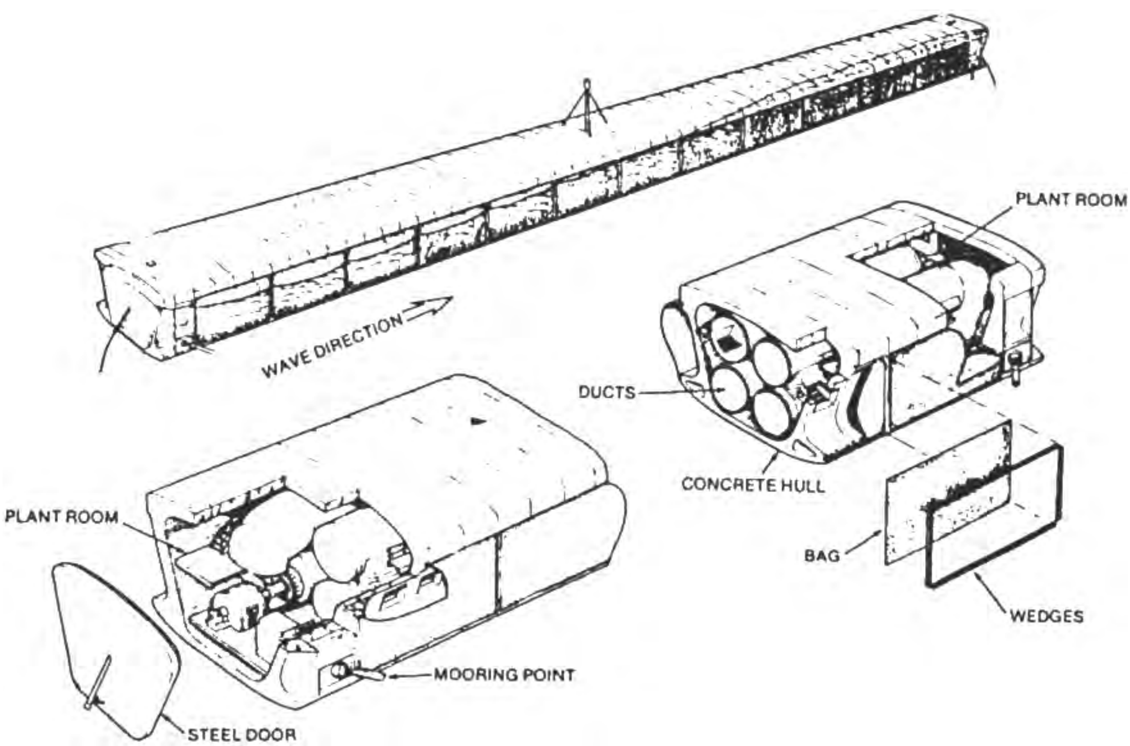


Figure 4. The French air-bag scheme as designed by Wave Power Ltd. after their work on rafts. The structure faced end-on into the prevailing wave direction. Waves compressed the bags on each side as they passed along. Air went through non-return valves to a common turbine.

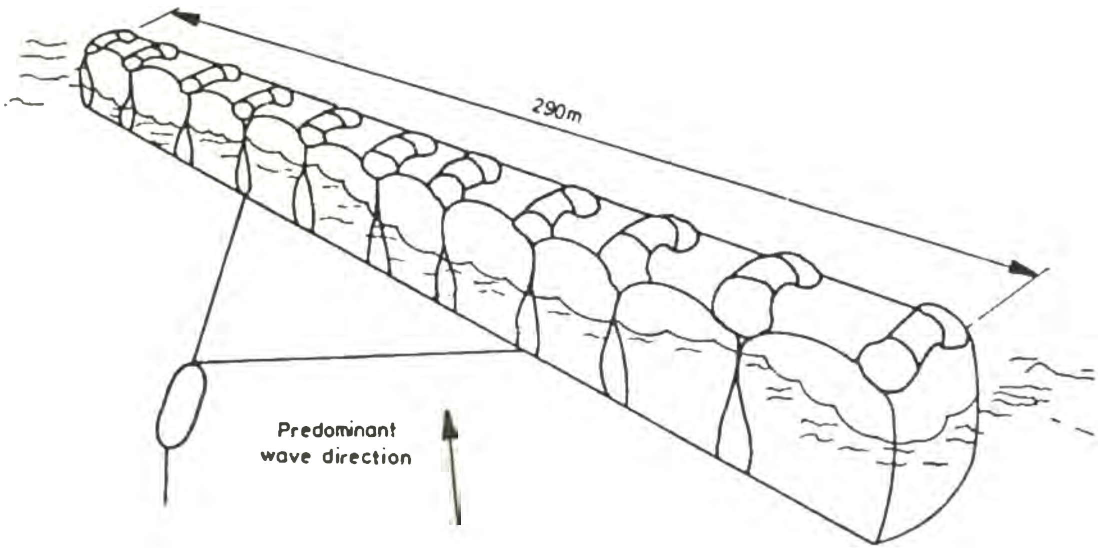


Figure 5. The SEA Lanchester team preferred bags on just one side of a structure lying oblique to the wave direction, and individual turbines. Since then they have moved to a circular plan form.

compressible: any volume which is squeezed in one place must squeeze out at another.The ideal destination would be to another bag driven by a wave 180°C out of phase and this has led to the phase-spanning bag designs. The rather low swept volume tempts the designers to use higher than optimal values for the damping coefficient. The volumetric difficulty has so far prevented the design of a point-absorbing bag.

Unless there is enough reserve of buoyancy in the form of an equal volume of solid structure above the surface, there is a risk that the entire device might sink under a wave large enough to act on all the bags at the same time with a pressure which might approach one atmosphere. The buoyancy reserve suffers unproductive fluid loading in addition to the energy-generating loading on the bags. Users of exposed turbines in oscillating water columns have reported that their equipment can digest salt spray and even, to my surprise, green water without damage. This means that what seemed to be one of the chief attractions of bags may be unnecessary. However if bag structures were designed to use tension-leg moorings instead of ballast and spare buoyancy, their very low material content could turn out to be valuable.

Hard-skinned devices avoid the problems of buoyancy loss and can have swept volumes which are much larger than those of their own structures. While they lack the highly desirable speed increase given by the section change of an oscillating water column they allow easier access to the flexible control of hydraulic technology. This can provide benefits described in the section on power take-off.

The most serious drawback of hard-skinned devices is that they nearly always require bearings which must work in sea water. This problem needs to be given very careful thought. One can attempt to take land bearing technology and provide adequate sealing. Alternatively one can start afresh and design a bearing which could only work in water. This has been done by Colin Anderson at Edinburg[30] who has developed a new type of bearing which uses ferrite magnets and enhanced squeeze films to support ducks on their spines. A test of a true marine design is to ask the question 'would it work ashore?'.

One of the early hard-skinned devices was the wave contouring raft developed by Sir Christopher Cockerell, the hovercraft pioneer. In its original form the Cockerell raft consisted of a 2 dimensional mattress with power take-off elements at the links. The geometrical problems of following wave curvature in 2 dimensions reduced the design to a 1 dimensional chain of rafts. Tank tests showed that similar extraction efficiencies could be obtained by reducing the number of elements in the chain to 2 with a larger rear one providing a reaction frame for the smaller forward element. The rear element provided a second desirable feature by suppressing the transmission of waves to leeward and forcing the presence of a node in the wave pattern, which was an ideal water motion for the front raft.

The development team took measurements of angular motions between raft elements and the required values of torque. In moderate seas the angles were small and so it followed that hinge torque had to be large. Things were improved if the size of the front raft was reduced but this led to the problem that in extreme seas the forward raft could capsize on to the rear one. The research team abandoned their work and joined forces with Michael French on the development of his air-bag design. The raft idea was stopped because of the sad fact that for much of the time waves are not very steep yet sometimes they can be very steep indeed.

A second early hard-skinned device was the buoy developed by Budal and Falnes shown in Figure 6. While buoys have been considered by many inventors the Norwegians made two notable new contributions. The first is the theory of point absorbers which they produced a few months before independent work by David Evans in Bristol and by Newman and Mei at MIT. Most people would have expected that a wave device would make a good attempt at extracting the energy contained in a width of sea-front equal to its own dimensions. This is not true. Budal and Falnes proved that the theoretical limit for an isolated symmetrical device depends on the wavelength of the incident waves rather than any dimension of the device: it ought to be able to extract energy from a width of wavelength divided by 2. For an isolated asymmetrical device this width is double, i.e. the wavelength divided by. When this theory was accepted wave engineers began to talk of 'capture width' rather than efficiency so as to avoid claiming values above 100%.

The point absorber technique cannot be pushed too far because of the limits of linear theory. Very small absorbers would have to move very large distances or be used only infinitesimally small waves. Furthermore it becomes difficult for very small devices to have natural frequencies in tune with the useful part of the wave spectrum. In small model tests, the gain of point absorber effects can easily be masked by viscous friction or by vortex shedding near any sharp corner. Nevertheless I have seen tank models moving with 13 times the amplitude of the waves which are exciting them. Arrays of point absorbers can mutually enhance their performance for selected combinations of wave direction and length.

The small body detuning problem led to a second of the many Norwegian discoveries – the principle of latching, which is discussed in the section on power take-off.

Another hard-skinned device which at first sight might appear to be symmetrical but which behaves in an asymmetrical way was invented by David Evans at the University of Bristol. It consists of a cylinder mounted below the surface as shown in Figure 7. The Evans cylinder was unusual in that it progressed much further than any other device on mathematical analysis. Theoretical efficiency curves were produced before any tank tests. But when these were carried out the test points came out extraordinarily close to the Evans predictions.

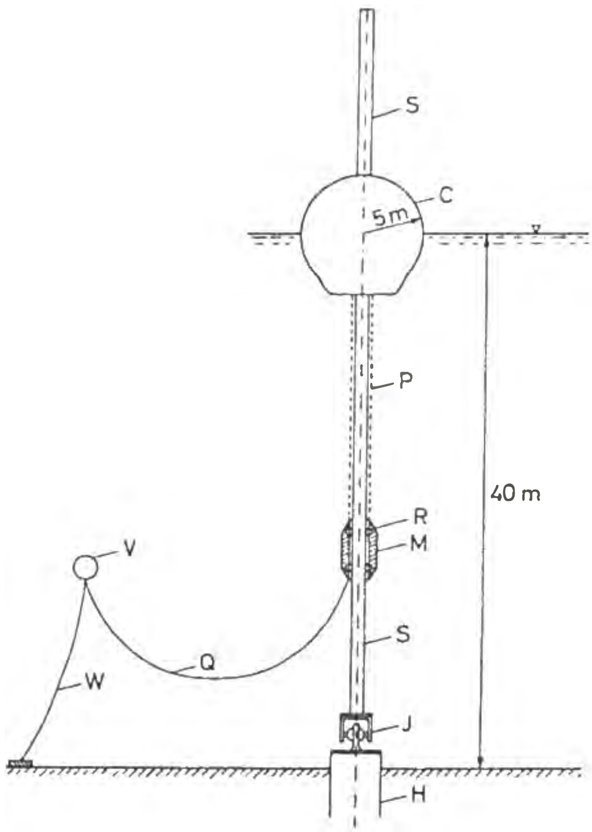


Figure 6. The Budal and Falnes buoy obtained very good power-to-mass ratios by using "latching" to extend low frequency performance. In this version the power take-off was by means of air pressure driven by an internal water volume.

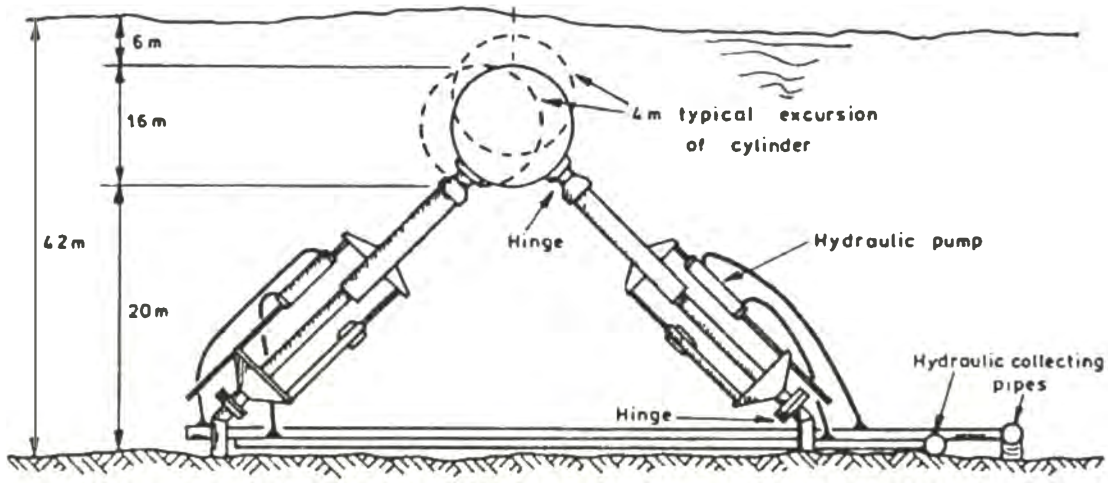


Figure 7. The Evans cylinder combines two axes of movement to cancel the onward transmission of waves. Sea water is pumped to a common manifold and a large Pelton wheel shared by other units.

An easy way to understand the operation of the Evans cylinder is to imagine that it is being used in reverse as a wavemaker. A sinusoidal vertical motion would produce waves which are symmetric either side of the device. A horizontal motion would produce waves which are anti-symmetric. When both motions are combined the radiated waves add on one side and cancel on other. The combination of these two translations produces a circular motion which satisfies the requirement for asymmetry and avoids the volumetric problems of the bag devices. What makes for a good wavemaker works as a good wave absorber when used in reverse.

My last example of a moving hard-skinned device is the duck which was developed by a team at Edinburgh University, the civil engineers John Laing and the electrical consultants Merz and McLellan[31] [32]. The forward part of the duck was designed with the idea that one should allow the water to move in a pattern as close as possible to the way it likes to move when one wave passes energy to the next. A rotary movement was chosen to avoid end-stops and the exposure of bearing surfaces. The back was designed to be coaxial with the center of rotation so that moderate rotations of the body do not create waves behind. However very large rotations do transmit waves astern which has the effect of reducing the mooring force. A bulge was added on the top to provide buoyancy so that the duck would just, but only just, recover from capsize. The forward water line length – which we define as the distance from the vertical through the axis to the front of the duck – plays a powerful role in determining the angle and torque for a given wave amplitude and hence the proper damping coefficient. Short water lines, say 0.6 of the back diameters, make the duck move with quite high angular velocity through large angles in small waves but with reduced torque. This shape would be used for vapor compression desalination(33) in which we want a large swept volume against a very low internal pressure difference. The penalty is that the short duck soon runs out of angular range. For electricity generation in rougher wave climates a longer water-line length – perhaps 0.9 of the back diameter – allows operation in bigger waves at the cost of higher torque requirement. Very long water-line lengths would lead to torques similar to those needed by Cockrell rafts.

The high position of the center of gravity of the duck, the forward water-line length, the moment of inertia and the added inertia of the water around it combine to define the natural nodding period. The added inertia of the water around the duck is at a minimum for the wave period which best matches the shape of the duck movement. For longer waves there is an extremely convenient increase of added inertia which broadens the band of resonant operation. Further broadening is achieved by changing the phase of the power take off force(34) so that lower frequencies have a component of negative spring while higher ones have a component of negative inertia. This technique is known as reactive loading or phase control.

A device in which the interface does not move is the Norwave Tapchan or tapering channel invented by an expert in mathematical optics Even Mehlum. The first prototype, built by Selmer Furuholmen has, been operating at a site near Bergen since 1985. The interface is a funnel-shaped channel blasted out of the rock to a carefully calculated shape with dimensions suitable for resonance with the local wave spectra. The funnel concentrates the energy from a frontage of about 60 meters. In shore of the funnel is a long smooth-walled tapering channel cut 7 meters below sea level and built up to about 3 meters above. This performs the function of rectification: waves from the funnel enter the channel and propagate along the channel. As the walls narrow the wave height increases until the water reaches the top of the wall and flows over it into a storage lagoon with an area of 8000 square meters. Large waves overtop early and deliver a large volume of water. Small waves must travel further along the channel before they get high enough to reach the top of the wall but nevertheless nearly all waves deliver something. This marks the difference between Tapchan and earlier over-topping schemes with walls parallel to the beach. Water flows out of the lagoon back to the sea through a 350 kilowatt Kaplan turbine. The lagoon stores enough water for the turbine to run synchronously at a constant power output – entirely suitable for slender electricity networks.

I believe that the Norwave Tapchan is the most successful of all wave energy projects to date. It runs unattended and Norwave claim excellent capacity factors. In the first prototype near Bergen the rock blasting work was less accurate than it should have been. As a result, more energy is reflected than is desirable. This will be improved for the plant being built for Bali and the efficiency of future units should be much better. The main problem with the design is that not all wave fields have the right geographical combination of deep water, hot-spot enhancement, blastable cliff and a storage lagoon. It may be possible to use a free-floating funnel as both a concentrator and a reaction frame for other types of wave device. Experiments at Edinburgh University have shown that such a funnel is stable, will concentrate and can be quite easily moored. It will however be very difficult to launch and so we are looking at ways to build it in water.

The ideas of the resonant gully and the oscillating water column have been combined in a project led by Trevor Whittaker from Queen's University of Belfast(35) as shown in Figure 8. The team found that there are many suitable gullies on the west coast of Scotland and have selected one at a convenient hot-spot site near Portnhaven on the Island of Islay. Civil construction of a 100 kilowatt device should be complete during 1988.

The occurrence of gullies close to hot spots is frequent enough to suggest the possibility that they have been produced by the extra wave action.

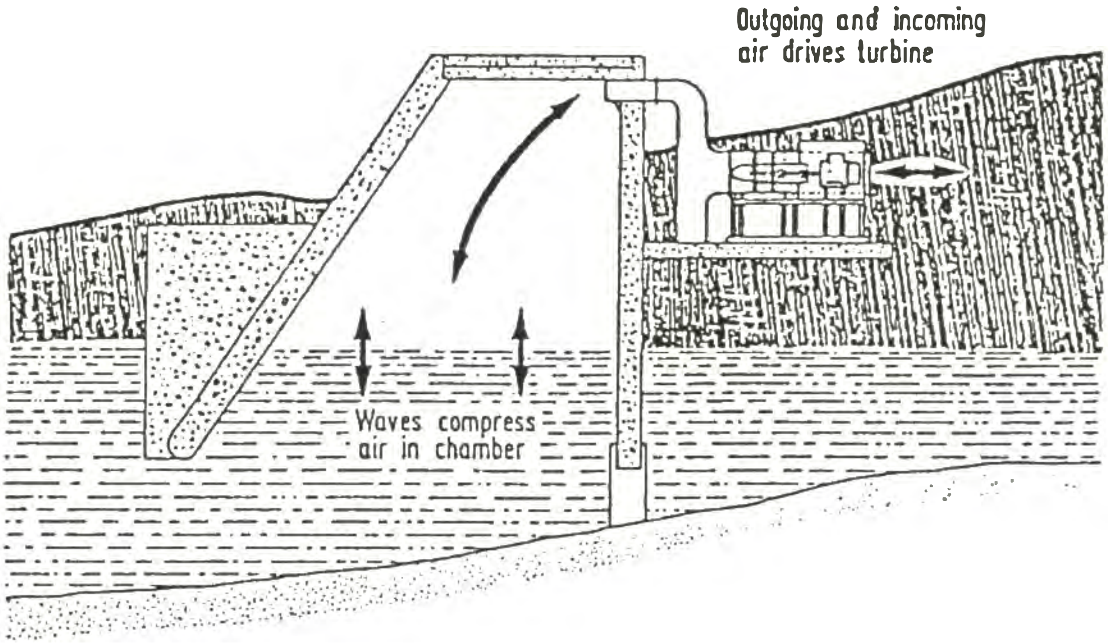


Figure 8. The Queens University oscillating water column which is being built in a gully on Islay, Scotland. Construction should be complete during 1988.

## Means of reaction

It is easy to make a structure which is moved vigorously by sea waves. Indeed it is quite difficult to make one which is not. But if useful work is to be performed then the large forces induced by the waves must be opposed. Several methods can be used.

The easiest and, so far, the only one to be used for full-scale prototypes is to attach the structures securely to the land – and preferably to land with features which resemble the requirements of wave power device. Not only does shore basing save money but it allows easy and frequent visits by maintenance engineers, politicians and potential customers. I am quite sure that it is by far the best choice for early wave power devices. There are however some drawbacks. It is not easy to accommodate a large tidal range. The material strength and exact shape of rock faults may be uncertain. The need for periods of fine weather for construction runs counter to the requirement for the persistent wave conditions of a reasonably firm power source.

These difficulties can be solved by careful site selection, rapid construction techniques, flexible schedules or mobile wave shelters which can be moved from site to site. Even Mehlum of Norwave has proposed that his Tapchan design could be built in the sheltered conditions inside a coral reef and then exposed by blasting a hole through to the open sea. A similar technique could be used for oscillating water columns which could be entirely excavated from the right type of cliff. It may be possible for careful survey work with laser and sonar devices to allow a structure built in the convenience of yard conditions to be towed to site and fitted to a cliff face as a dentist will add a porcelain inlay. All the advocates for shore mounting agree that, in the longer term, the objections to it are the limited number of possible sites, the attenuation of wave energy over any shallows and complaints from other users of the coastline. When we run out of places with deep water close to deserted cliffs with the right geology in a good wave climate, it will be time to move out to sea.

Offshore devices can obtain reactions through connections to the sea bed or to elements in water which is moving in a different way.

Good examples of the sea bed attachment scheme are the tension legs of the Evans cylinder and the vertical spar of the Budal and Falnes Buoy. The two schemes are distinguished by the values of the static loading. The strut of the Budal and Falnes buoy has to resist only the tensions and compressions imposed by the power take-off mechanism and indeed for later versions they designed a mechanism entirely contained in the buoy.

It is my belief that the technology of permanent sea bed attachments has suffered from the applications developed for the offshore oil industry which are usually in sedimentary rocks, sand or ooze. Most sites with good wave climates have been scoured clear of sand and ooze out to depths of about 80 meters or perhaps more for longer wave periods. The Lewisian gneiss of the Hebridean wave field has a high crushing strength. I understand that both coral and lava, which occur in many island sites, are also suitable for post-tensioned pile heads.

Reactions obtained by coupling to water have followed nearly all possible routes. We can go downwards, sideways or backwards or in an oblique combination of sideways and backwards. We can use cables in tension only, legs in compression and tension combined, or beams in a combination of bending and shear. If we move downwards we can find calm water fairly close to the surface because the attenuation of wave motion with depth is rapid. If we move backwards we need to go at least half a typical wavelength. If we move sideways we must move one or more crest. The difficulty is that statistical data on crest length are not as well understood as those for wave length.

The elements through which we make connection can be compact, like tension cables, and so attract very little fluid loading. Alternatively they can be beams, stressed in bending and shear which are less mechanically attractive than purely tensile members but can make up for their disadvantage by themselves being useful energy-producing devices. Beams can be essentially rigid or can contain elastic, yielding joints.

Because of yet another Norwegian invention, it is possible to make a magic "sea-hook" which obtains a compact local reaction to wave force by using the action of the wave itself. This works much more succesfully than attempts to lift oneself by one's own shoe laces! Kjell Budal[36] realized that he could use the Magnus effect on a horizontal spinning cylinder to generate a lift force at right angles to the local rotating velocity field of a wave. This lift acts parallel or anti-parallel to the water acceleration field. It is the water acceleration which largely determines the loading on wave devices, and the Magnus-Budal lift will add or subtract from it according to the direction of spin. The velocities involved are of the same order as the wave frequency, and the power needed to rotate a thin sleeve round the cylinder is very small compared to that in a typical wave. It should be possible to induce the spin by using tangential jets.

The first deepwater oscillating water columns proposed by the British National Engineering Laboratory coupled their structure to a plate deep enough to be in calm water. Sir Christopher's raft reacted against a plate astern. Both approaches led to rather large structural masses. Another backwards approach was used by Michael French for the attenuator configuration of his air bag device. He planned a rigid concrete structure of the order of a wavelength long which lay parallel to the direction of wave propagation in what is known as the attenuator configuration.

In a scheme which followed his air bag, Michael French proposed an array of surging bodies separated by distances of the order of half a wavelength which worked against pumping elements in adjacent neighbors. While tension works superbly through cables it is much harder to provide a compression. It would therefore be necessary to arrange for an overall tensile bias.

The approach used for the Edinburgh Duck was to use a sideways connection parallel to the wave crests. A large number of ducks were mounted so as to rotate about a circular spine which was longer than several wave crests in what was called the terminator configuration. The idea was that, by sampling a rich variety of wave phases, the average wave forces would cancel out and the spine would therefore provide a relatively stable reaction frame. We knew from the outset that the bending moments would be our greatest problem and, even before we made any force measurements, we were certain that some form of non-destructive yielding would be necessary. The best way seemed to be to assemble the spine from sections with joints. We feared that the limitations of material rigidity might spoil the efficiency of the ducks and so we built a special mounting rig for narrow tank tests which could have its elasticity and yield points varied by electronics and servomotors. David Evans predicted that reducing the mounting stiffness in long waves would improve efficiency. His predictions were correct and allowed us to doulbe performance in very long waves – 25 times the diameter of the duck. The two extra axes of movement allowed the backs of our ducks to copy the behavior of the Evans cylinder. This is easily done in the convenient surroundings of narrow tank and one can prove that, given enough computing power, it is also possible for ducks on a long 'intelligent' spine described in the next section. Unfortunately we were never given the chance to try.

Elementary analysis of a rigid beam subjected to the bending moments of a single wave crest in the middle and troughs at each end would suggest that the bending moments would rise with a high power of length and be largest in the middle. However we calculated that for a much longer spine – spanning many crests – with a moderate degree of compliance, the bending moments would be greatest about half a crest in from each end. We expected that the central region would have fairly constant bending moments which would be independent of length.

It needed a specially constructed wide tank with multi-directional waves and an extremely sophisticated model to confirm these predictions. The model consisted of up to sixty jointed sections with bending moment sensors at each joint. The signal from each bending moment sensor was used to calculate a command signal for a servomotor for each joint, which moved it through an angle corresponding to the required elasticity. We believe that this was the world's first computer-controlled beam.

We also found that very long spines had extraordinarily low mooring forces which reduced slightly in very large seas. The model could accept a high casualty rate in its mooring lines. Fatigue predictions for the electrical connection to the sea bed showed that existing cable types could be used with a factor of safety of several hundred.Long spines allow very large amounts of power – hundreds of megawatts – to be collected into one cable and they make the best use of every millimeter of sea front. The full scale design provided control of spine stiffness and non-destructive yielding by means of hydraulic rams at each joint. In large seas the rams contributed a fair amount of useful power. With hydraulic joints there is no longer any problem about bending moments because they are directly related to oil pressure in the hydraulic rams and entirely under control. It would be possible to alter the maximum allowable bending moment by a single computer instruction. However the area of anxiety switches from bending moments to the magnitude of the necessary joint angle. The time-table laid down by the UK Department of Energy required us to produce full-scale designs for an enormous 2000 megawatt scheme before, rather than after, the tank experiments. We had to make a very difficult guess at the value of the necessary joint angle and settled on 12 degrees for a 90 meter distance between joints.

The ultimate test of this guess was to find the joint which suffered the biggest angular movement and program it to simulate a failed hydraulic system. Then we drove the wavemakers to produce the steepest possible wave with a height equivalent to the maximum that was predicted to occur in 50 years in mid Atlantic aimed exactly at the most sensitive joint. Even at a scale of 1 in 100 the wave is impressive. It can capsize trawler models bow over stern. But it moved the 'damaged' joint through only 4 degrees. We had a factor of safety of 3.

The first duck designs produce their power with pumps placed between duck and spine. This led to the possibility of very large torque reactions in addition to the bending moments. It proved possible to eliminate these torques and to provide completely sealed working conditions for the power-conversion mechanisms by reacting the duck torque against a gyro-stabilized frame(37). The idea of using gyros at sea is by no means new and goes back to 1904(38). Much bigger gyros than the ducks need were successfully used for ship stabilizing in the Thirties(39). However the proposal aroused a good deal of skepticism. The reliability experts wanted to apply the environmental factors for "exposed ship" conditions to the vacuum sealed interior of the power conversion canister and the costing experts insisted that the case must be costed at £10,000 per ton rather than the £850 per ton of a reputable manufacturer.

A solo duck on tension-legs can manage without gyros at the cost of mechanical penetrations of its casing. The necessary torque reaction could be obtained from lines to a torque arm as shown in Figure 9.

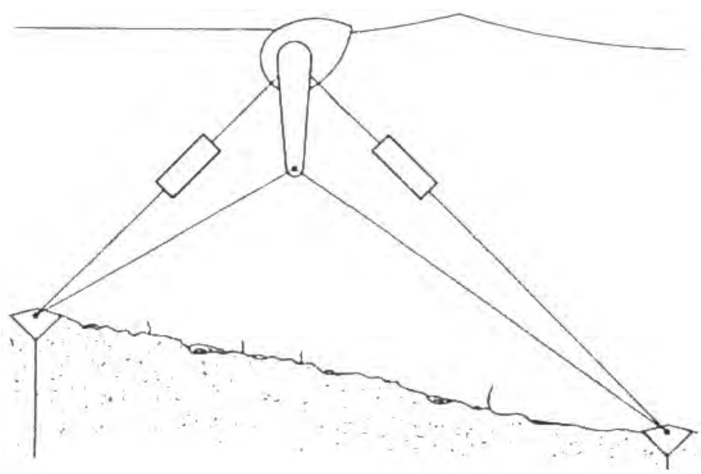

Figure 9. A solo duck on tension-leg morrings with the torque reaction provided by an external arm. The complication of gyro reaction is removed at the cost of mechanical penetrations which must be sealed. The boxes in the upper two lines contain hydraulic mechanisms for yielding and elasticity control. Tests in extreme waves show very little force the upper right quadrant.

Another duck design intended for wave-powered de-salination by the vapor-compression method shown in Figure 10 works against the internal rotary inertia of a body of water inside[33]. It is difficult to get enough inertia to develop the full torque, but for the vapor pumping duty the main requirement is for swept volume. Michael French has gone on to consider action against an internal masses constrained by linear slides and variable springs[40]. I am sure that he will be giving his end-stops very careful attention!

Another group at Lanchester Polytechnic has tried to use a simpler philosophy for the Clam[18] using crest-spanning spines with a shorter, rigid, unjointed length. They found that lengths which were long enough to be stable suffered bending moments in extreme seas which were dangerously high. With lengths short enough to be safe they found that the spine movements and the higher coherence of the waves over the set of air bags spoilt their efficiency. Arranging the spine at an angle helped but they have now adopted the circular configuration[41] first proposed by Masuda.

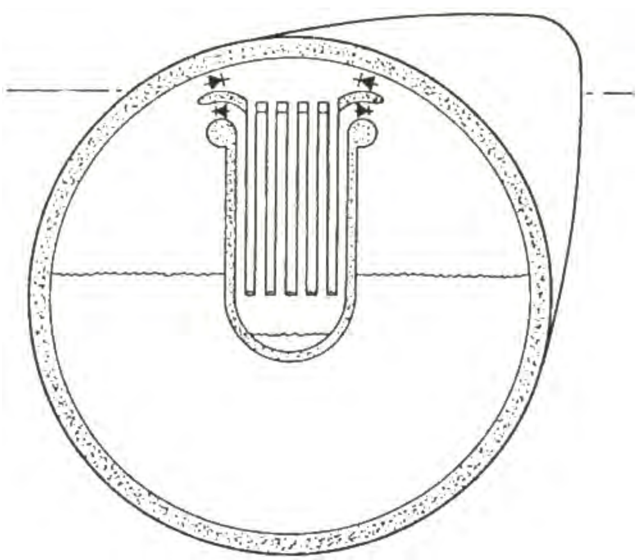

Figure 10. A short-beaked duck intended for wave-powered desalination reacts against the inertia of an internal water volume. This acts as a slow but very large displacement pump. Fresh water production would be about 1/1000th of the swept volume of the pump and could be 100 tons a day even in tropical wave climates.

## Power Conversion Mechanisms

Despite the diversity of interfaces all wave power devices share common objectives in the design of their power conversion systems. The alternating movements of the waves must be rectified. The forces presented to the water must be of the correct magnitude and in phase with its velocity. The power train should provide an increase of velocity to levels suitable for electro-magnetic generation. Electrical output must be of the correct frequency and voltage to allow connection to a network of other generating plant.

It is regrettable that the power in waves comes in such spikey pulses with time intervals of half the wave period – say 4 to 7 seconds. Figure 11 shows a computer simulation of instantaneous power values and their mean. It does not help very much to add the random outputs of many different, uncorrelated wave devices. Figure 12 shows the combination of 64 separate devices which would still be an unacceptable input for a small island network. However about one hundred seconds of storage will produce a completely steady output from a single device in any typical wave spectrum.

The built-in storage feature of the Tapchan lagoon makes it particularly attractive for island use. The power conversion system designed for the duck used the gyros as energy-storing flywheels which could hold 45 minutes of full output. This was far more than enough to run the electrical plant at the synchronous speed of the mainland grid, and reduced all the downstream costs by a factor of about three. The earlier the storage mechanism is placed, the cheaper are the later stages because they work steadily at mean output.

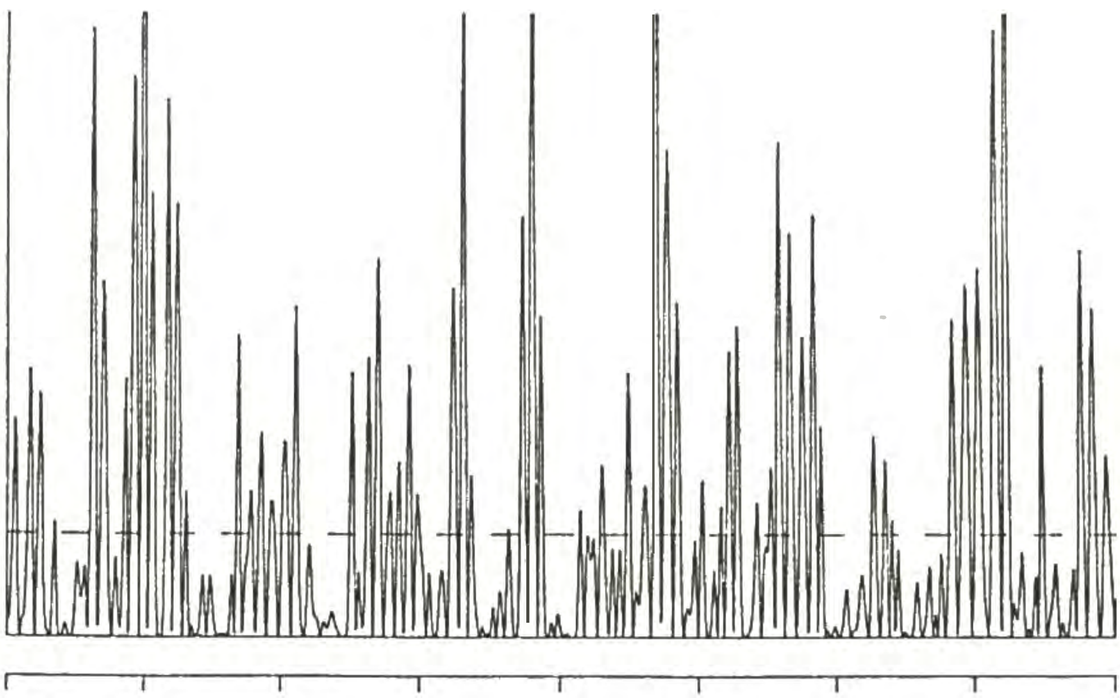

Figure 11. The instantaneous power output of the wave record used in Figure 3.The signal has been clipped at 7 times the mean value and would have exceeded this level 5 times during the 8-minute run.

sleeve choke-valve which shuts off the air flow if it seems to be getting too fast. Other possible solutions to the problem are designs of aerofoil section with delayed or modified stall characteristics, biplane configurations with more than one row of blades, a mechanism to accelerate the turbine back to its working speed quickly, or even a mechanism to vary blade pitch through the wave cycle. The latter proposal, due to Professor Falcoa of Universidade Tecnica at Lisbon, would lose the simplicity of the Wells concept but might provide the chance to apply more advanced control strategies. This loss of simplicity is an almost universal feature of technical advance which, in general, I would applaud. But even if, as I believe, the future designers of such a turbine can solve the formidable problems of bearings subjected to such large centrifugal loads, nobody will have the least doubt about the pedigree of the "non-Wells" Wells turbine.

For work to be transferred from one object to another it is necessary for some force to be in phase with velocity. This occurs when a system is excited at its natural frequency and some damping mechanism is applied. If the size of a wave power device is reduced, its natural frequency rises and wave forces on it become more in phase with position rather than with velocity. Budal and Falnes devised the scheme of latching their buoy[45] so that it could not move until a large wave force had built up and then releasing so that its velocity was more in phase with the wave force. This allowed a much smaller buoy to extract energy from long waves, leading to good power-to-mass ratios. Various attempts are being made to include latching mechanisms in the design of oscillating water columns.

The Evans cylinder uses pumping elements in its tension legs. The use of two sets of power take-off pumps with a 90 degree phase shift between their deliveries is a unique and valuable power-smoothing feature. The pumps fed sea water to a common manifold shared by other cylinders and a large Pelton wheel which ran at synchronous speed. I believe that for solo use in a smaller installation, high-pressure oil would be an interesting alternative. If rotary pump/motors were driven by flat tapes wrapped round their circumference, the extra range of movement would make it possible to lower the cylinders during typhoons and avoid all the extreme loads.

The Edinburgh team were the only group to go for high-pressure oil power conversion in the face of very strong preferences for low-pressure air and high-pressure sea water. It allowed us to apply computer controlled torque limits, the best damping coefficients, reactive loading and any further hydrodynamic tricks which have not yet been discovered. High-pressure oil is used in nearly every other application where large forces must be controlled in an intelligent way and often where high reliability is needed. Naval guns, ship-stabilizers, mining equipment, machine tools, earth-moving machines, flight controls, power-sterring and vehicle braking are typical examples. Oil hydraulics are used for driving wave-makers in big test tanks and even for driving the reciprocating airflow rigs used by the fervent advocates of low-pressure air turbines. But the official reliability experts advised our Department of Energy that non-return valves would be more reliable in unfiltered sea water than in our micron-filtered oil!

Despite all these apparent advantages we found that there were no hydraulic systems powerful enough and that, while the efficiency of existing equipment was much better than that of any air turbine, it was still not as high as we would have liked. This should not have been a surprise although Langley and Maxim had flown quite heavy models with steam power, steam engine technology could never be suitable for aircraft. Specially designed petrol engines had to be developed and the investment in new aero engines has been increasing ever since.

A small improvement in the efficiency of any element in the power train of a renewable energy system will multiply the value of every preceding part of the structure. We therefore designed new types of hydraulic machinery with a much greater emphasis on conversion efficiency. We used hydrostatic bearing technology to separate every moving element. This meant that the working life would be indefinitely long – as long as we could keep the oil clean. An account of the development of a high speed variable pump/motor used for driving the generator and the energy-storing flywheels is given in reference[(46)]. A 600 kilowatt prototype was built at Edinburgh University. Low power measurements of static leakage at high pressure and shear loss at high speed fulfilled all our hopes about very high efficiency. We could demonstrate full separation of the hydrostatic bearings and even rotate by hand a pressurized machine at zero displacement. But we have been unable to raise money for high power tests and so the work is at a standstill.

It was also necessary to design slow, very high-torque pumps with variable delivery. The torque of a hydraulic machine is the product of its volumetric displacement times the pressure difference across its ports divided by 2. If the displacement can be varied then the torque input to the pump can be controlled and many improvements in the hydrodynamic conversion efficiency of a wave device can be achieved. Unfortunately all the existing variable-displacement machines are high-speed, low-torque ones. Again, we had to design something new.

We based our pump on the ring cam configuration. Most ring cam machines have a number of cam lobes which face radially inwards from a ring which forms the outer body of the pump. Each lobe operates a number of rollers in sequence. Each roller passes the cam thrust to a pumping module. This means that each module is operated many times for one revolution of the pump. For very large sizes it may be better to use a duplex configuration like that of Figure 13 where the forces act axially through the thickness of the cam.

The controlling design parameter is the Hertzian stress at the contact line between the rollers and the cam surface. By choosing the right materials and heat treatment and using values for the Hertzian stress which are much lower than those used for railways, we should be able to make the fatigue life of the combination sufficiently long.

The outlet valve on each pumping module is of conventional design. But the inlet one is specially modified to provide displacement control. Each valve has an

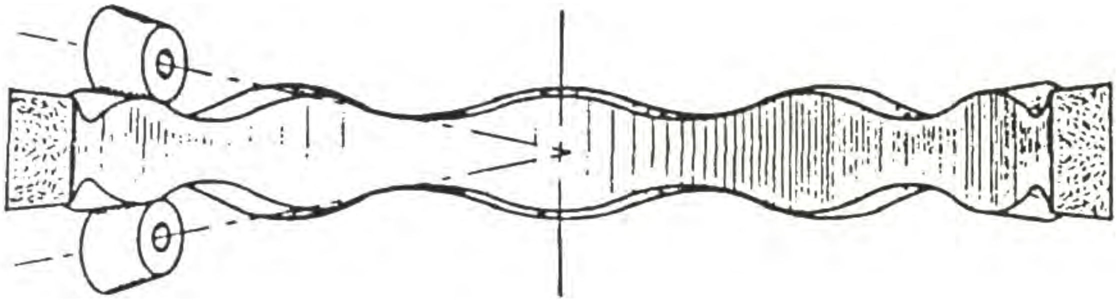

Figure 13. A duplex ring cam. The pumping modules are driven by each lobe via conical rollers running on the cam surface. The Hertzian stresses must be kept low enough to allow about one billion operations.

electromagnetic latch which can hold it open for any selected operation of the module. The delivery of the pump is reduced in proportion to the number of valves which are disabled. Prototype valves have been built and are being fitted to a small test pump. Measurement of the breathing loss of the inlet poppet shows that it is less than 1/1 000th of the power delivered by an enabled module.

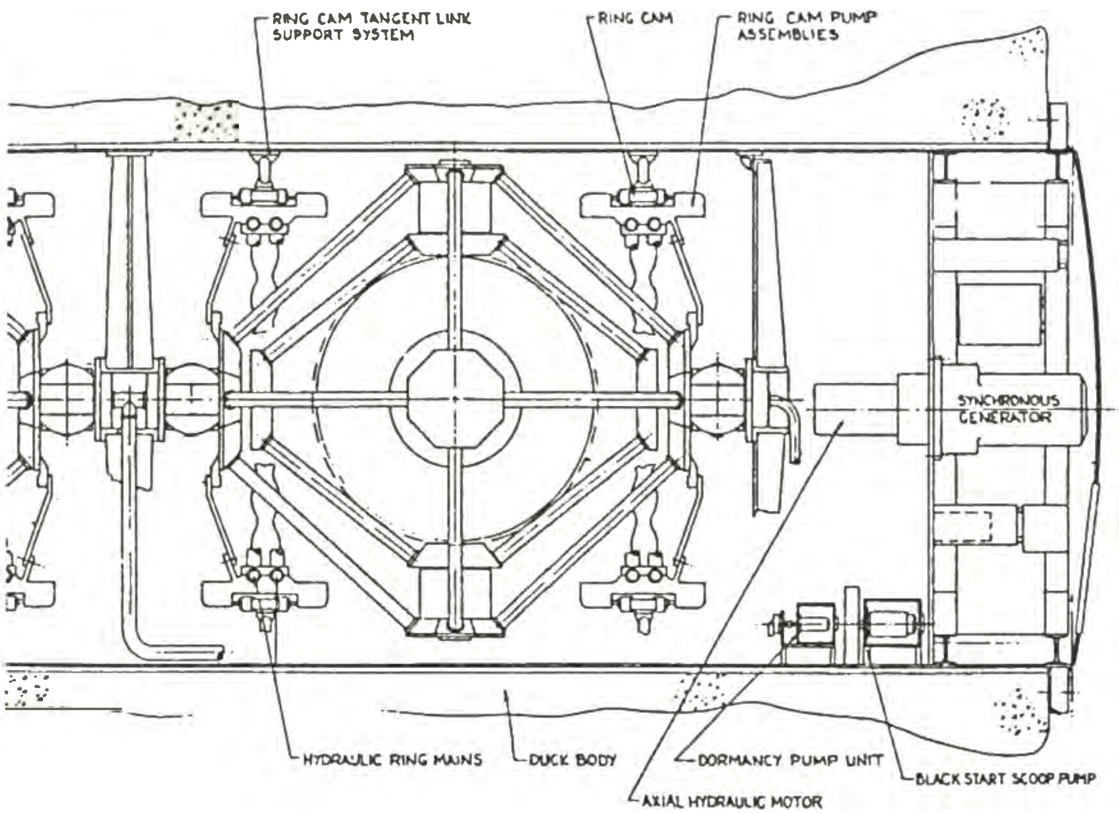


Figure 14. Half a duck power-canister showing how the ring cams move around the gyro-stabilized gymbal frame. Each duck has two pairs of contra-rotating gyros.

The cost of ring cam pumps will depend on the sum of the costs of the cam lobes and pumping modules. But the value depends on the product of these numbers because each module is operated by each cam lobe. This means that it pays to make the cams as large as possible. Units with the torque needed for ducks would weigh very much less than gear boxes of equivalent torque. Work passes through as many as one hundred lines of contact instead of only five in a epicyclic gear train. Moreover, while it is not possible to skip a missing tooth in a gearbox it is quite easy to avoid using a damaged lobe or pumping module.

When the energy flux is above its average value, the excess flow from the ring cam pumps drives axial-piston motors which increase the gyro speed slightly. During a lull the axial-piston machines are used as pumps and keep the energy output steady. The inside of the power canister is evacuated to about 1 mm Hg with a residue of carbon dioxide. This provides almost ideal working conditions for hydraulic machines. The motion of the duck can be reduced to $2^{\circ}$ in sea states up to 0.6 meters rms by controlling either the spine joints or one of the canisters. This allows a damaged canister to be replaced.

## Materials

The first aircraft were built with bicycle parts, wood, piano wire and fabric. The first all-metal aircraft did not emerge until the 1930's while some wooden designs lasted until the end of World War II. Learned papers are still being published on the aluminum alloys while composite plastic materials are being increasingly used. New materials for aircraft are being developed 8 years into the history of aviation and will continue to emerge.

Wave energy will follow a similar path and must start with materials that are available now. These are chiefly steel, concrete, textiles and rubber. Perhaps a wave-oriented review of these familiar materials will highlight the needs of the future.

Steel fabrication has been highly automated in advanced ship yards and is used for a wide range of quickly designed and easily modified structures. Parts can be cut away and drilled. Extra lugs can be welded on with wonderful convenience. I am sure that the first experimental prototypes ought to be made from steel.

But the fatigue endurance limit of steel which occurs in dry air does not apply in seawater and the fatigue life of bare steel is not satisfactory. The preparation for proper paint protection is expensive and even the best paints can be damaged during the removal of marine fouling or through careless handling.

Wave power devices do not need as many internal compartments as ships, indeed they would be much better without the stresses caused by hydrostatic pressure over panels. Furthermore the energy needed to process steel is much higher than that needed for concrete. But in the long run, the energy arguments will be decisive. I predict that mass-production wave devices will not be made from steel unless its metallurgy changes a good deal.

Concrete ships have been built during steel shortages and ferrocement is successfully used for yacht hulls and even canoes. Most grades of concrete have excellent endurance (except in heavily polluted tropical water) and superb strength in compression. Unfortunately the tensile strength is low and unpredictable, so that most designers assume that it is zero. The normal density is 2400 kg/m$^3$, which is not heavy enough for a good clump anchor but requires the provision of buoyancy compartments for floating structures. The density can be reduced by the addition of foaming agents which entrap air bubbles so that floating objects can be made without any internal compartments. Foamed concretes have very low thermal conductivity which may make them useful for thermal processes such as direct wave-powered desalination. Unfortunately the foaming process can increase porosity and the long term buoyancy may be questionable. It is well known that the tensile weakness of concrete can be overcome by internal steel reinforcement. By far the most efficient method is to use post-tensioning strands of high tensile wire to bias the concrete halfway up its compression strength range. Some built-in srping element should be included to maintain tension even if the concrete shrinks. The steel does not fatigue because it stays under nearly constant stress. The concrete does not fatigue because fatigue is a tensile phenomenon. Indeed if the cement-to-water ratio is kept rich, any cracks which do form will heal themselves.

A major part of the expense of one-off concrete structures is the shuttering into which the concrete is poured. With long production runs shuttering can be much more elaborate and its cost can be shared over all the items produced. For construction in remote island sites it may be that a combination of ferrocement and post-tensioning could be used with a minimum of capital cost but a higher labor requirement.

In the first official cost-estimating exercise of the British wave programme the figures for concrete were based on estimates from a group of civil engineers with relevant experience. The cost depended on whether construction took place over water or ashore and also on the difficulty the various shapes. In 1981 money the cost of material poured on shore was £24 per tonne. Allowances for reinforcement and shuttering etc. raised it to £75. The addition of 4% by weight of post-tensioning steel raised the price to about £150 per ton for highly stressed parts.

In 1985 these first cost-estimating rules were abandoned by the Energy Technology Support Unit at Harwell who replaced with their own figures. To our concern, the cost of concrete was raised from £75-£150 to £400-£600 per ton. This large increase produced predictable changes in the electricity cost. Readers with their own opinions on cost for concrete can factor the ETSU estimate for wave electricity cost accordingly.

What wave power needs is a material with the cost, permeability, pourability and endurance of normal concrete but with a density just less than that of water. We should have a moderate but consistent tensile strength and a clear fatigue at say 5N/mm$^2$. Perhaps these properties can be achieved by finding a way to change the shape of internal fissures or by the addition of a fibrous filler. It is curious that a frozen mixture of water with a few percent of pulped newspaper seems almost ideal: the energy needed to keep a large marine structure refrigerated is a tiny fraction of the output of a wave device.

Wave engineers are hoping that the development of fibers such as ICI's Parafil and du Pont's Kevlar will continue and that tension legmoorings with neutrally buoyant ropes will become cheaper. When a company has risked large sums over many years in the development of a new material it will naturally set the highest price that the market will allow and keep very quiet about the true production costs. This means that one should avoid using cost estimates based on the most advanced technology and look instead at products which are facing competition. With superfibers inside rubber sheets it may be possible to make devices with water-filled bags.

## Survival

Oceanographers can predict with confidence the height of the largest wave which will occur during some long period of observation and their predictions for the Atlantic seemed quite terrifying to early wave pioneers. The height for a 50-year period of mid Atlantic conditions is 34 meters from trough to crest[5]. A wave of this size has in fact been observed in the Pacific by the USS Ramapo in 1933.

For objects the size and shape of typical wave devices, forces depend mainly on water acceleration. Linear theory predicts that they should be in proportion to the first power of scale rather than being determined by the square law which applies for forces related to fluid velocity. If a wave power engineer could choose the perfect climate he would choose a wave height of about 3 meters so that the extreme Atlantic wave induces forces about 10 times larger than those which one would like to have. If this factor of 10 is multiplied by further factors of safety – some marine engineers suggest a factor of safety of 5 – the result is a structure which is needlessly expensive for most of its life. It seemed clear to me that one should never try to resist forces which were greater than those which occurred at the maximum power output of equipment. I wanted all the critical stresses under my control, not under that of the waves.

The structural stresses due to wave loading can be separated into two types. There is the spot pressure variation which is applied and resisted locally. This is often less than the static pressure at the lowest part of a device and generally of very little concern. We need a local impact strength much lower than is required for a wind turbine blade working in rain let alone hail. Expanded polystyrene foam is not quite strong enough but wood, concrete and steel are all much stronger than necessary. The only exception to this rule is for concave shapes into which a wave breaks trapping air. This can induce very high instantaneous pressure oscillations. If all the outside surfaces are convex this slamming does not occur. Longuet Higgins has suggested that material behavior under spot loading can be tested by dropping water from a height equal to that of the wave. The problems arise when

Newtons per square millimeter are multiplied by many meters i.e. when wave loads induce bending moments in long beams, high towers or thin panels.

A wonderful advantage that waves offer over nearly every other source of loading is that there is an absolute certainty that the force will be reversed within a predictable time so that it can be dodged by yielding through a predictable distance. The mechanisms which allow this yielding to occur may well look complicated. But the leading technology of every generation would always look complicated to the previous one. We are moving into an age when material costs will rise but, because of computer-controlled machine tools, complicated parts are getting relatively very much cheaper to produce.

My colleague Jamie Taylor did an extensive series of force measurements in a narrow tank with freak waves hitting ducks on rigid mountings placed at a succession of positions relative to the breaking point. The ducks capsized completely in waves much smaller than the freak and thus presented the wave with a stubby aerofoil shape which prevented any square-of-velocity forces from adding to the acceleration ones. He found that force coefficients calculated by dividing maximum force by wave height were *lower* in the biggest waves than in the small ones. A set of synchronized photographs showed dramatic foam and crashing breakers when the force gauges showed very little loading while the highest values nearly always occurred in the apparent calm of a wave trough.

A similar result was obtained with bending moments measured in multidirectional seas in a wide tank using circular spine sections. Retzler added a variety of appendages to our spine model. He found a similar reduction for shapes with a low freeboard but, for high freeboard shapes he found that the linear-theory first-power rule applied. Forces and moments seem to rise with the first power of wave height to the point that waves go over the top of the structure. From then on it seems wave height to the power 0.8 fits the observations best. This is good news for low freeboard devices like the Evans cylinder and the duck because 10 to the power 0.8 is only 6.3. This is not much bigger than the factor of safety that is often applied when people are ignorant of stresses or the properties of their materials. It is quite proper to argue that by understanding fluid loading more thoroughly one can reduce factors of safety to much nearer unity. Indeed where unmanned plant is under consideration it is possible to argue that there should be a small but finite risk of failure comparable to that, say, of ship collision.

I am indebted to Denis Mollison for an exact expression for the optimum factor of safety. His relationship assumed Guassian uncertainties of loading and structural strength and included terms for the cost of an accident and the incremental cost of extra strength. For many months I kept the expression programmed in my calculator and applied it to any possible situation. Despite the use of accident costs which were very high, reflecting American levels of legal damages, loss of national prestige etc, the best factor of safety was often less than 1.5. It was also interesting to see the high value of any reduction in the uncertainties. Factors of safety are really factors of ignorance and lead directly to factors of waste.

**Some advice to potential customers**

The capitalist industrial system seems to dictate that the effort that goes into selling will often exceed that which goes into research and design. Glossy brochures and smooth public relations are often substituted for detailed drawings and tests for fatigue. But to spot the flaws in the sales patter you need to know much more about the technology in question – perhaps not quite as much as you would need to design and build the equipment yourself, but certainly a good deal of it.

There are particular dangers associated with quotations of cost per kilowatt of output capacity. The practice derives from the descriptions of fossil plant which supposedly works at its rated power level for as long as fuel is supplied. But most renewable energy sources (geothermal ones are a notable exception) work at variable rates and the number which happens to be printed on the generator nameplate means almost nothing. It costs very little – perhaps less than $30 per kilowatt – to fit a generator of twice the size, but all that this will do is to halve the capacity factor. (This is the amount generated in a long period divided by the amount that would have been produced if the plant had run at its maximum.) Indeed over-size generators may lose energy because the constant losses of an electrical machine which are caused by windage and iron magnetization become quite significant at small fractions of maximum output. Costs per kilowatt are quite meaningless, and even dangerously misleading, unless coupled with values for a capacity factor.

It is important that this capacity factor should refer to a representatively long period, not just the most favorable months of the year. It is often informative to compare values for productivity claimed by plant manufacturers with those published in the accounts of the Utilities which take their output. Remember that 'hours in operation' do not imply 'hours in operation at full output'. Be cautious of figures for cumulative lifetime generation if this is not accompanied by a clear indication of how long that life has been. If energy generated is given in millions or even billions of kilowatt hours you should remember that there are rather a lot of hours in a year. You should divide the energy by 8760 (or 8766 if you want to be more accurate about leap years!) and then by the power rating to get a capacity factor and sometimes a surprise. The public relations departments of the less productive plant seem to believe that their readers are unaware of how many hours there are in a year. Another questionable practice is to quote output in terms of the number of homes supplied*(43)*. Sometimes this presentation will take the *peak* nameplate output and divide it by the *mean* domestic consumption. One should also scrutinize closely the nature of previous sales. Sometimes a manufacturer will sell to a company which he also owns. Sales which are shortly followed by the bankruptcy or takeover of a supplier are poor evidence for the true capital cost.

There is a certain safeguard which will work even for the newest technologies having no previous track record. This is to accept at face value the salesman's data and invite his company to both build and operate the new plant at their expense. You offer to pay for all the energy at a rate which would be profitable if their figures are correct. The sales agreement can include options for purchase after a few years and clauses about staff training for your own people. By that time you will know enough to design and build your own – better – system and sell them back to Britain.

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