PROCEEDINGS

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Proceedings of the Wave Energy Conference
London-Heathrow 22-23 November 1978

This document provides a record of the papers presented at the Conference. The papers, and statements made during discussion, do not necessarily represent Government or Departmental policy.

The 1978 Wave Energy Conference was sponsored by the Department of Energy and organised by the Energy Technology Support Unit, Harwell. The Proceedings have been edited by Peter Quarrell, a consultant from the P-E Consulting Group attached to ETSU.

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PREFACE
Dr J K Dawson (Head of ETSU)

These Proceedings are a record of the Wave Energy Conference held at London-Heathrow on 22 and 23 November 1978. The Conference was sponsored by the Department of Energy and organised by ETSU; there were 205 delegates, including 45 from 14 overseas countries. I should express our thanks to all the contributors who presented or introduced papers, and to those who took part in the discussion.

Research on wave energy has continued since the Conference, with special emphasis on cost reduction, where there has been some progress. The KaiMei has put to sea again, with the UK turbine installed on schedule, and results are being collected. International interest in wave energy is increasing, and a number of countries are beginning to finance programmes of research and development.

The information in these Proceedings will be supplemented by a general review paper on wave energy which ETSU has prepared. It will be published shortly in the Energy Paper series by the Department of Energy; copies will be available from Her Majesty's Stationery Office or any bookseller.

The Energy Technology Support Unit (ETSU) acts for the Department of Energy. Besides the development of renewable energy sources, of which wave energy is one, it is also responsible for research, development and demonstration related to energy conservation, and for developing a strategy for energy research and development in the UK. More information about ETSU's work can be obtained by writing to us at the address on page 146.
The UK wave power programme was conceived four years ago. Few people took it seriously before that time and it is really only in the last two years that the programme has begun to take shape. What have we achieved in those two years or so?

Firstly, there is the asset of a team of some 150 people all over the country, in small firms and large firms, in universities, in government laboratories, who are gaining a grip on this new and difficult technology of wave power.

Secondly, in that time we have moved from elementary testing in the laboratory to very sophisticated testing that simulates in miniature real sea conditions. The films of this work are very striking indeed. Along with this has gone an enormous development in our understanding of the subject – still not great enough, but as the Conference will show, a substantial step forward in our knowledge. And we have taken some early wave device designs into real sea conditions at the 1/10th scale, we have learnt to drive a small wave power station and as one of the teams said recently, we have generated the odd megawatt-hour. The films here are also quite dramatic.

Thirdly, we have from the start insisted on a proper engineering evaluation of concepts as they arose. To ensure that all our widely dispersed teams were working against common evaluation criteria, we employed firms of engineering consultants experienced in appropriate disciplines. In close consultation with teams they have produced so-called reference designs, and have costed them. So it is that we are today able to give some costings for the first generation of wave energy machines.

This procedure of introducing proper engineering evaluation is I am sure correct. However it does focus attention on the problem areas. Indeed, there is usually a stage in the research and development of technology at which the problems loom larger than the solutions and things appear to change from month to month and possibly from week to week. Wave energy is currently at this stage.

The knack of management of such a stage is to stand back from the detail of the problems and to try to pull out the broad messages for the advancement of knowledge of the subject. This is what I believe those on the national wave energy programme are now doing.

I make these preliminary comments because wave energy has so many enthusiasts and so many sceptics. It would be quite premature for them to allow the results to be described at this Conference either to damp their enthusiasm or to vindicate their scepticism. There is still a major amount of work ahead before firm conclusions can be reached about the future of the technology. But realism must tell us that any talk of a full-scale or near full-scale energy station out at sea by the early 1980s is premature. We still have to evolve concepts and engineering designs that would justify the major expenditure that would be involved in such a step.

The problems that we now face in harnessing wave energy are broadly as follows:

The size of resource

A year ago we thought that the annual average energy in the incoming waves might be in the range 70 - 90 kW/m of wave front. Today, we believe that the figure is nearer 50 kW/m in the area where devices would be deployed. However, this is still an important area of discussion, calculation and measurement before we can be sure. But even 50 kW/m is a large and useful resource if we can capture a good proportion of it.

The directionality of the waves

Most of the 50 kW/m, or whatever it finally turns out to be, is in waves coming from distant storms perhaps a thousand or even several thousands of miles away. These distant storms may occur anywhere over the very wide Atlantic area. Simple geometry tells us that we cannot hope to capture all the 50 kW/m from such a wide angle with a line of wave energy devices. This will cause a further reduction in the size of resource that can be captured by the devices in such a line. Mr Russell and some colleagues will talk about both these important features tomorrow morning.

Problems flowing from the characteristics of the wave resource itself

Waves are slow, random and irregular in their movements; these have to be converted to fast and regular movements in order to produce electricity. In some of the devices it is proving extremely difficult to devise an efficient mechanism for making this conversion. This particular problem is not so serious in other devices, namely those from the National Engineering Laboratory and the Hydraulics Research Station, which involve the direct use of air or water turbines. The use of such turbines coupled with the ideas for lighter structures that are emerging from the universities seems to provide one basis for on-going developments. This important problem will be considered in each of the device presentations today; and then first thing tomorrow morning Mr Glendenning will provide a coherent overview of the area, including the possibility of using energy carriers other than electricity.

Anchoring, mooring and environmental problems

The problems of anchoring and mooring these devices could further limit both the size of resource that can be tapped and the cost-effectiveness of the overall system. Quite a high proportion of the cost, up to about 1/5th, is absorbed by anchoring and mooring in the device designs that require this feature. Some designs can incorporate sea-bed mounting of the device, but it is by no means clear that this provides a cost-effective alternative to the anchoring-mooring problem. What is clear is that this is a topic of increasing importance. Mr Hancock will talk about it tomorrow morning.

Wave energy devices are likely to be mounted or moored up to 10 miles offshore and the associated environmental problems have been examined. Such problems will exist but the present judgement of the Advisory Group examining this is that they are unlikely to prevent wave energy devices being placed at sea although there can be limits on the density of
placing them. These problems are reviewed in Dr Dawson's paper tomorrow afternoon.

The high costs of the early designs

The resource is relatively diffuse and to capture it large areas of device have to face the on-coming waves. The early devices provide these large areas either with large amounts of relatively low cost concrete or with smaller amounts of higher cost steel, or some combination of the two; whichever way, the designs are proving expensive. Estimated costs per kW installed are currently in the range £4000 - £9000 compared with £500 - £1000 for a fossil or nuclear station. The consultants to the Wave Energy Steering Committee, Rendel, Palmer & Tritton, will review their analysis of the early devices after the individual device reviews this morning and afternoon. And tomorrow morning Dr Smith will discuss the basic structural design requirements of wave energy devices in general.

Several approaches to solving the high structural cost problem have been suggested. One in particular, by Professor French of Lancaster University, has been examined and shows promise for reducing the costs to perhaps £1700 per kW installed. But our knowledge of this device is at a relatively early stage and one must be cautious until more work is done and its feasibility confirmed. It and some other new devices in our programme will be described later this afternoon. Still further devices, sponsored by the Science Research Council, will be considered tomorrow.

Putting all these factors together, variability and directionality of the resource and the problems of energy conversion, one finds a station load factor very much lower than one is used to in modern conventional stations, say 0.2 compared with 0.5 - 0.9. Such a load factor taken with the high capital costs already mentioned, gives rise to an estimated cost/kWh for the electricity which is very high, in the range 20 - 50p for the early designs, (compare an overall average generating cost at present of about two pence). It is true that with some of the important concepts and designs that are emerging, one can hope for a reduction to below 10p/kWh and perhaps considerably lower. But these concepts still have to be turned into acceptable engineering designs before their basic feasibility can be judged.

Wave energy is very much at an early stage of technical development compared with the other alternative energy sources. And in case you feel I have dwelt too much on the problems, let me end on a more positive note. These results could not have been achieved in the time or for the cost without a high scientific and engineering quality in the work, considerable dedication by the many teams in industry, universities and government laboratories, and sheer hard work. The resulting team is now very much a corporate one, with much interaction between the various geographical centres around the UK. It comprises a substantial national asset, and given continuous Government support it is determined to find solutions. The natural resource is there and if anyone can learn how to capture it this team will.
THE DEVELOPMENT OF THE WAVE-CONTOURING RAFT
Sir Christopher Cockerell, M J Platts, R Comyns-Carr (Wavepower Ltd, Southampton)

The wave contouring raft system is the outcome of ideas initiated and developed by Sir Christopher Cockerell from 1972 onwards. His object was to develop a wave energy device which is within the bounds of current technology and capable of collecting low-density energy over a wide area. It should consist of simple, relatively small units, amenable to quantity production, which would enable a power generating system to be built up and commissioned in stages according to needs and production capability.

This thinking led to the investigation of chains of pontoons, hinged together so that the passage of a wave down the chain causes the pontoons to oscillate relative to one another. Energy is extracted from the sea by applying a torque about the hinges to damp the motion.

Early experimental work in 1973–74 indicated that if the scale of the device is correctly matched to the local wave climate a high efficiency can be obtained in the sea states where most of the energy is concentrated.

For the last two years Wavepower Limited have been financed by the Department of Energy to examine the feasibility of the Cockerell raft for converting the energy of sea waves into electricity on a scale that would make a useful contribution to the country's energy needs.

The work has involved extensive model testing in the wave tanks at British Hovercraft Corporation's laboratories, the building and testing of a 3-unit 1/10th scale power generating installation in the Solent, and design studies for a full size installation for Atlantic conditions.

Hydrodynamic model studies

An essential feature of a wave energy device is that it should spend much of its time working at optimum efficiency extracting energy from small and moderate sea states, but that it must be able to survive much more extreme conditions. Typical figures for Atlantic waves show that whereas the annual average power rating might be 80 kW/metre of wave front, powers as high 10 MW/metre can occur for short periods. In such conditions 'efficiency' means little and all attention is focused on survival. Our testing has tended to separate these two issues using models at two scales, 1/50th and 1/100th. Figure 1 shows a 1/50th scale model on the left and a group of 1/100th scale models on the right.

At 1/50th scale the test tanks at British Hovercraft Corporation's laboratories are capable of producing waves that cover the working range, and we can test power production efficiency. At 1/100th scale the same waves go well beyond the normal peak conditions and allow the non-linearities of survival behaviour to be fully explored, looking at mooring forces, hinge forces, etc.

At 1/50th scale, much effort has gone into parametric modelling of power take-off systems – so that the model could represent the characteristics of a full size power generating system. Indeed it has been important to be able to model a wide range of characteristics, because it is quite easy to postulate many different power absorbing mechanisms, and it is necessary to know how the choice of parameter settings affects other design requirements.

For modelling the characteristics of the system at 1/50th scale, we used electronics. The power mechanism shown diagrammatically in Figure 2 is driven against a resistive
Raft efficiency in irregular waves

![Graph showing raft efficiency in irregular waves](image)

Figure 3
torque by the rotation of the hinges. Different power take-off characteristics appear parametrically as different patterns of resistive torque loadings. The technique chosen to explore this was to sense the rotary motion of each hinge on the raft model using the motion transducer and from that signal generate a controllable resistive torque on the electric motor geared to rotate with the rotary motion of the hinge. The electrical control loop from the motion transducer to the resistive motor then contained two differentiations to get velocity and acceleration and several parallel feedback loops with controllable gain. By switching in the appropriate loop it was possible to generate torques simulating a spring, velocity proportional damping, friction and inertia. A further addition has been a variable current limit to the motor which effectively simulates a controllable torque limit.

The 1/50th scale model tests show (see Figure 3) that a high efficiency is obtained at moderate wave periods where most of the energy lies, but that the efficiency falls off in the long period waves encountered in the less frequent storm conditions. Thus the device sheds power before it reaches the power take-off system, which means that this can be more economically designed than the range of powers in the sea would suggest.

Several basic features of the rafts have proved encouraging in showing them to be relatively insensitive to changes in design parameters. First, raft weight makes little difference to power performance above a certain minimum figure required to maintain proper hydrodynamic contact with the water. It has been suggested that this is because the added mass of water acting with the raft is four to five times the mass of the raft itself and this dominates the motion once the minimum raft weight is exceeded.

Second, the rafts are insensitive to the form and value of the damping produced by the power take-off. The results of tests using velocity proportional damping in regular waves show that power performance is maintained for quite a wide range of damping either side of the optimum. Similarly, changing to a square wave, constant torque form of damping results in a more jerky raft motion, but the power is still produced with only the loss of a few per cent.

Third, the rafts are insensitive to marine fouling. A layer of artificial grass was attached to the underside of the rafts, to simulate seaweed. This dropped the performance by only about 1%.

Fourth, the form and position of the mooring does not affect power performance significantly.

Fifth, although the early test models were made in up to seven sections with six hinge lines, it was soon found that there was very little gain in power from having more than two hinge lines. In fact recent indications are that at least comparable performance can be obtained from configurations with a single hinge line, but possibly having more than one leading section. Such an arrangement offers many advantages and our studies are therefore moving in this direction.

It is pleasing that all the tests so far have indicated a simple, insensitive device with a good overall performance. There are other features still to investigate but these are unlikely to affect the simplicity of the basic raft unit.

The Solent trials

Encouraged by the 1/50th and 1/100th scale model tests Wavepower Limited have built and installed in the Solent an array of three rafts, designed for 1/10th scale to correspond with the Solent wave climate which has waves about 1/10th the size of those experienced in the Atlantic off the Hebrides. Tests have been conducted, first with a single raft (shown in Figure 4) and later with all three in a line.

These trials are acting as an extension of the laboratory work; exploring raft performance in real, irregular and multi-directional seas; measuring power performance with a realistic kind of power generation mechanism — also measuring hinge loads and mooring forces.

Three rafts were chosen so that the centre raft would be properly representative of a raft in a string of rafts, and so that the problem of mooring adjacent rafts could be explored. 1/10th scale is big enough to give a wealth of sea-going experience, while still being small enough to handle, and for boat-scale seamanship to apply.

The Solent trials site provides a wide range of wave conditions and directions covering the lower three-quarters of the scatter diagram at 1/10th scale. A few miles away in Christchurch Bay there are much bigger waves, equivalent to about 1/5th scale. At a later stage in the programme it is planned to move one raft to this location for a test of survival, linking it up to the recording system on the National Maritime Institute's experimental tower.

The centre raft of the three is fully instrumented with the remaining two rafts capable of being instrumented at a later date if this should be required. The general instrumentation consists of load cells on all six mooring attachment points with a seventh at the sea-bed end of the forward mooring line, a vertical accelerometer on the front section of the raft, looking for high body acceleration associated with general
slamming loads, and strain-gauged hinge assemblies. The power generation unit is also fully instrumented. An inertial unit measures all six degrees of motion of the central section of the raft. We also measure sea data with a wave probe that can tell us the height and direction of the waves.

Signals from the raft are fed through sheathed cable along the sea bed to a barge moored adjacent to the rafts. Here they are processed, along with wave, tide and wind data, by a data collection system. The system multiplexes the data onto a magnetic tape recorder for later processing by shore-based computer. Simultaneously an on-board computer computes simple statistics of each channel (peaks, means, standard deviations) in engineering units, giving an instant feel for each run.

The power unit is shown in Figure 5. An oil hydraulic system has been adopted with double acting rams hounted over the hinges and arranged to act as reciprocating pumps to feed oil from a pressurised tank to an accumulator and thence to a piston motor driving an automotive alternator. The load is provided by a series of low voltage lamps.

As at the model scale, a great deal of thought has gone into the design of the power system so that a variety of types of damping can be applied to the hinges. The two most useful operating modes provide firstly, constant power operation and secondly, constant torque operation. The levels of torque and power are set remotely by the operator.

The testing programme aims to cover the whole area of the scatter diagram provided by conditions in the Solent, including variations of wave direction, taking 20-minute records with different damping settings in each particular sea state.
Figure 9 shows tests on a single 1/10th scale raft in the Solent in seas of approximately 2.5 seconds period, 0.5 m significant height generating about 1.5 kW at the hinge.

Figure 10 shows similar conditions, with three rafts on location; complete removal of damping load allows the raft to move more, but the motion is still quite safe, and the rafts can be boarded and inspected.

Full-size studies

Development from small scale studies to a full scale power installation suitable for, say, the Atlantic environment west of the Hebrides, involves matching both the hydrodynamic design of the device and the rating of its power conversion system to the local wave climate. The criteria for the two cases are rather different.

In the case of the hydrodynamic design one is aiming for maximum efficiency in that part of the wave scatter diagram where most of the energy lies. The frequency scale of the raft response varies directly as the length of the raft. The power capture, for rafts of the same proportions, varies roughly as the cube of the length. Unfortunately the latter is also true of the loads on the hinges and moorings. The choice of raft size and of raft spacing, is likely to be a compromise between the desire for the greatest energy extraction from a given wave front, the limitations of engineering feasibility, and economic optimisation.

The relevant wave data for this area consists mainly of some long-term data from Station India, further west in the Atlantic, where the annual mean power in the sea is about 80 - 90 kW/m, together with some recent data from a buoy moored off the Hebridean island of South Uist, from which the predicted annual mean power is 43 kW/m. The disparity between these power levels indicates one of the present difficulties involved in making any firm estimates of output from a wave power station in this area.

It appears at this stage that optimum raft length will lie between 80 m and 120 m. Our current design studies are based on a length of 100 m and a width of 50 m.

A first visual indication of the likely matching between the performance of a 100 m raft and the energy in the sea is seen in Figure 11. Lines of constant electrical output from the raft are plotted over the wave probability contours, the one on the left being for Station India and the one on the right for South Uist.

In the case of the rating of the power conversion system one must take into account the variable nature of the power source from minute-to-minute, hour-to-hour, day-to-day and even year-to-year. There will be occasional periods -- several days per year -- when a wave energy station could collect power several times greater than the mean power available throughout the year. Intuitively it is not economic to rate a power conversion system to match these high powers, as it would be under-utilized. It is appropriate to design the system for some level less than the maximum power available to it, and to design the control system to protect it from overload by deliberately reducing efficiencies or dumping power at each raft.

A typical rating of the system might be about 2.5 MW output per raft. This is a long-term, say hourly, rating. In general, component ratings will be set by cooling requirements and efficiency considerations, and some degree of overload will be possible. When heat build-up is the limiting factor the acceptable overload will be time-based. In other cases absolute limits will be set, for instance on generator speed and turbine choking. Because the power in the sea fluctuates about the long-term average on a minute-to-minute basis, this capacity for short-term overload must be used to achieve the highest possible long-term average output.

Statistical smoothing between rafts in a group will ensure that the overall power level in the collection system will fluctuate much less than the fluctuations of individual rafts, but a detailed assessment of this requires knowledge of the spatial distribution of power variations along a line of rafts and this is not yet available.
Figure 12 shows the yearly mean outputs per metre width available from rafts of different sizes, with different power cut-off levels, based on the long-term wave climates predicted for Station India and South Uist.

These values are yearly mean outputs for an average year. There will be years with higher mean outputs and years with lower mean outputs. This yearly variation will be an important consideration in wave energy economics.

From Figure 12 it can be seen that a raft with a high hourly mean rating will be uneconomic if it fails to generate enough additional power to pay for the added expense. An increased rating adds some increment to the cost of the power components but not necessarily to the cost of the hull or moorings, or the laying procedures at sea. It is too early yet for benefits and losses of this kind to be evaluated. Equally, the optimum size of raft is not obvious. Individual raft component loads reduce dramatically with size, reducing unit costs, but this is balanced by the need to handle more rafts at sea.

Power generation

The input to the raft’s generating system is in the form of variable but generally slow and small oscillations at the hinges – usually less than about 10° to 15° either side of the mean. Correspondingly high torques must be applied to extract the power. However, under storm conditions hinge motions may occasionally rise to 25° or more and the excess power must be rejected in some way to avoid overloading the generation system.

To obtain the best hydrodynamic performance the torques applied to the hinges need to be varied approximately in proportion to the significant wave height. Also, if the raft has more than one hinge line, then the torque on each one should be capable of independent adjustment. This is because the proportion of total power absorbed by consecutive hinges changes with wave period. With the appropriate torques applied to the hinges the amplitude of hinge motion at a particular wave period is also proportional to wave height.

For an articulating raft system a range of alternative approaches are available for converting the power as shown in Figure 13. However, several of these have features which are unacceptable for electricity generation.

Firstly, on the basis of current technology the option of a direct connected reversing generator operating at the speed of raft oscillation is ruled out by its cost and weight. A speed-increasing system of some kind seems to be essential.

Power conversion alternatives

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<th>Raft length m</th>
<th>Yearly mean Power Output with cut-off levels shown</th>
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<th>Wave Station S. Uist</th>
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<td>50 KW/m</td>
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Figure 12

Secondly, the option of direct mechanical gearing to the generator has been discarded because it results in high mechanical inertia loading and intermittent electrical output with associated difficulties in generator control.

This leads us to some form of fluid transmission; the options available are shown in Figure 14. One option is to use oil hydraulics. However this technology is felt by us to be incompatible with the need for unmanned operation of large numbers of these devices, with infrequent maintenance in a marine environment. The rejection of excess power in extreme sea states could also be a problem with a closed-circuit system. An expensive seawater-cooled heat exchanger would be needed.

Fluid transmission alternatives

- Hinge motion
- Direct coupling
- Generator
- Speed increase
- Gearing
- Generator
- Fluid transmission to generator

Figure 13

Circuit
- Open
- Closed

Medium
- Seawater
- Air
- Oil
- Water

Pump
- Piston
- Vane
- Bellows

Turbine
- Reaction
- Impulse
- Axial
- Francis
- Turbine
- Pelton
- Turgo

Figure 14

One possible and attractive option is a simple open-circuit system shown in Figure 15. If seawater is used as the medium then the output from positive displacement pumps
driven off the raft hinges can be fed into a common reservoir from which it flows through a turbine coupled to an AC generator, the water finally discharging back into the sea. The reservoir allows the pressure level for a particular sea state to be built up and maintained so as to give a reasonably smooth output from the turbine on a wave-to-wave basis. If the system is designed for low head operation the reservoir can be open-topped and excess power in a storm can be rejected simply by overflow.

Open circuit seawater system

With suitable turbine control the torque at the hinges can be set by continuous adjustment of turbine flow to maintain the appropriate pressure upstream. If the raft has two consecutive hinge lines, differential torque settings could be obtained by off-loading part of the pump system on one hinge line, but this results in some complexity which may be avoided with a single hinge line.

This thinking has led to the arrangement in Figure 16. Two leading raft sections, each about 25 m wide, are connected along a single hinge line to a common back section. The pump extends right across the raft and forms an integral part of the structure. It takes the form of a double-acting oscillating vane pump for which the leading sections of the raft provide pump chambers and the back section provides a segmental hollow vane. The water flows from the pump into a transverse main connecting to the central reservoir. The turbine is vertically mounted under the reservoir and discharges below the raft.

Figure 17 illustrates the complete system. Flap valves are provided for pump suction and discharge. Alternate ports in the hollow vane connect the upper and lower sides of the pump chambers to the respective pairs of valves.

The turbine is an axial flow Kaplan type, which has the wide operating characteristic we need for efficient operation over the full range of sea states. The pressure is set by turbine vane control to match the sea state, and no other hydraulic controls are envisaged. A rim-mounted generator is shown but a bulb unit would be a possible alternative.

Figure 15

Figure 16

Figure 17

Figure 18
and the pump chambers. This scheme indicates the direction of development with regard to power conversion and raft articulation. It is still at an early stage and some of the implications for structural design have still to be resolved.

**Raft construction and maintenance**

Rafts are a familiar hull type with great potential for structural simplicity and can be constructed in either steel or concrete. We believe both have potential for development in this context and our policy has been to progress designs in both materials.

Firstly thinking about steel – in size the raft is similar to the bottom structure of a VLCC and our design consisting of a gridwork of transverse and longitudinal bulkheads at approximately 13 m centres would be easily recognised by any shipbuilder. The arrangement of bulkheads also proves convenient for the formation of ballast tanks – some 12000 tonnes of ballast water are required to bring the 3300-tonne steel hull to a draft of 3 m. The panels making up the bottom deck, side shell and bulkhead panels can be standardised for maximum interchangeability.

Figure 19 shows a typical bottom or deck panel and illustrates how these standard panels are brought together to form a rigid 3D structure. Sub-assemblies which are as large as possible are assembled from these panels before finally joining them to form the completed hull. This process of building up the structure from standardised panels offers great scope for a high level of automation.

A number of UK shipyards have semi-automated panel lines – Swan Hunter at Wallsend have a panel facility capable of handling 1500 tonnes per week for example – but none are sufficiently automated or have adequate covered facilities to obtain the full benefit of volume production. We are planning further studies to find out what a green field site factory might look like and to arrive at a better estimate for volume produced hull costs.

Corrosion protection forms a very substantial part of total hull costs, and a satisfactory solution of the corrosion protection problems to provide long maintenance-free life is fundamental to the use of steel hulls for wave energy devices. It is generally agreed that epoxy-resin-based paints backed up by a properly designed cathodic protection system can in principle have a 25-year life. Given good coating design, the main problems are associated with adequate preparation and control of application. To achieve the required standards of preparation and application, painting problems have to be carefully allowed for in hull design and a large covered painting hall will be required at the end of each sub-assembly line where blasting and painting of the complete sub-assemblies can be carried out under controlled conditions. The requirements go far beyond current UK experience and much further attention needs to be given to this area.

**Concrete**

On the other hand concrete is attractive as a hull material because of its durability and resistance to corrosion. Reinforced concrete ships built in the 1914-18 war have demonstrated hull lives of 50 years or more.

We have developed concrete designs in some detail. The disadvantage of concrete construction is that it is heavy. In particular, in this kind of hull form, solid concrete internal diaphragms add much weight. Thus we have recently been looking at composite structures, shown in Figure 20, which combine the excellent corrosion resistance of a concrete outer hull with the lightness of a steel space-frame inner structure. Figure 21 shows a 3D view of this form of construction.

In order to obtain the lowest possible hull and device costs the benefits of mass production must be fully exploited, and it is essential to integrate production considerations into the design at the earliest possible stage.

As little or no experience of mass production of large concrete structures exists, we have studied this aspect in some depth. Our construction programming work to investigate how quickly a raft might be built (assuming highly organised working procedures, carefully planned craneage and materials
barge and tugs would continue to be totally occupied producing replacement rafts, removing old moorings and rafts and installing new ones.

Hulls must be produced at a very high rate to achieve any significant power plant capacity and there will be a limit to the rate at which production factories can be built and commissioned. Figure 23 shows the total output possible from a programme starting in 1990 with one factory producing 50 rafts per year and adding one such factory each year until 1995 when 300 rafts per year are being produced. This is an arbitrary limit but it may not be unrealistic as a first estimate of national capacity. It would provide about 6 GW rated capacity installed by the year 2000 and about 19 GW final installed capacity by the year 2020 whereupon replacement begins.

Figure 23

The key assumption in the production and replacement cycle is obviously the design life of each raft. In many ways 25 years is an unrealistic assumption. Some components are not subject to wear and scarcely to fatigue, and it may be possible to gain a very long life indeed from much of the raft, by careful planning and major refits or even perhaps rebuilds of components and raft sections that have a limited life. It would then be possible to consider a midlife refit when certain critical components were replaced. Depending on the nature of the refit this could be carried out in a large floating dock which travelled along the site, or could be in a refit base to which rafts were towed.

In either case the refit facilities would begin life say 12 years after the production factory, and then proceed continuously at the same rate. A basic production module installing 24 rafts per year would have to be matched by refit facilities refitting one raft per week through a 24 week weather window.

Routine inspection is possible at two levels. A primary level of electronic surveillance would be an essential part of every raft, transmitting basic data to shore at regular intervals about the raft's integrity and performance. Such data would be used to monitor for unexpected damage needing emergency attention.

The second level of inspection and maintenance covers planned visual inspections and manual attention on a regular basis. This might be yearly or at longer intervals. It would require work boats to carry out a limited range of inspections and replacements only.

Limiting the regular maintenance and inspection to a tight schedule and limiting its scope, implies that additional fast, rough weather work boats would be needed to cope with emergencies. Since these boats would have a wider operating window than the others they might well draw on some of their crews, but it is unlikely that equipment appropriate to one use would match the other need.
Strategic considerations

The date at which installed capacity becomes available implies that any significant national contribution of energy has to be initiated 25-30 years in advance. Thus a useful contribution in the year 2020 implies a fully developed production and maintenance technology available by 1990.

This itself would take considerable development. A 10 year period at sea with prototypes is a minimum prerequisite, to establish the design in detail. If part of the requirement must be to develop preliminary production, installation and maintenance techniques, this implies building a significant number of preproduction rafts. A raft smaller than Herbridean scale could be developed much faster than a large one. Planned for some location such as the South West approaches or North Sea, such a size of raft could provide a floating test bed for both design and line production methods provided the raft is large enough to involve all the appropriate technology.

We have seen that one limit to the contribution that wave energy could make to national energy supply is that imposed by production rates, the ability to maintain devices at sea and the actual life of the devices in service. A second limit is provided by the total length of wave front along which the devices could be usefully deployed and the optimum rates of energy capture that could be developed in different sea areas. Techniques for estimating the total size of the resource on this basis are under development, but much more data on device performance in real seas and wave climates is needed before firm figures can be produced. The scale of the resource is not, however, the only factor to be considered.

At the present time the value of the wave energy contribution tends to be related to its ability to replace existing supplies based on the present demand and supply system, assuming a static pattern of end uses and their geographic distribution. Thus the current UK wave energy studies are mainly concerned with the supply of electricity through the national grid to existing demand centres. Yet we are necessarily looking 25-30 years ahead before there could be a major contribution from this source and many changes in the whole economic and social scene are inevitable in that period.

If the level of investment in wave energy development is to be related to its potential value at this time horizon then the scenario needs to be much broader and more dynamic for the evaluation to have any degree of realism.

It is not entirely apparent that electricity is the final thing to go for. Wave energy devices have the ability to produce energy in various forms, starting with mechanical work. One could perhaps use mechanical work directly in some way, or somehow use process heat, or hydraulic power, as alternatives to electricity. All sorts of things could be possible 25 to 30 years ahead. Production of intermediate fuels - hydrogen – is frequently discussed.

One very real possibility is desalination. The reverse-osmosis forms of desalination work from a high-pressure source of sea water, and use no heat; this is an obvious avenue for wave energy to explore. These wider questions need study, and it is both a part of the wave energy programme and in our own interest to continue to contribute to that debate.

DISCUSSION

M J Platts

I think that in most of our work mooring is the problem that still looms largest. There are two problems that conflict. One is that we wish to put the devices close together because we need to tap the power from as great a width of sea surface as possible; but from the model work we have done on mooring, the mooring forces are high and we wish to have a compliant mooring system in order to dodge extremely high snatch forces. Mooring devices close together means that you don't want them to move relative to each other too much and so these two requirements conflict. We have quite easily moored three rafts in the Solent adjacent to each other just using conventional mooring techniques, but this isn't really viable at full size. So we are looking at various levels of structural cross-linking between rafts and also at the technology of the moorings themselves. We are in the very large force range, and we need long lives and this takes us beyond the existing experience of the North Sea. The sort of things we are looking at are the use of cross-linking struts articulated at both ends, which merely stop the lateral motion, taking the lateral forces, then the use of hinges which allow the spine to articulate but take shear forces across preventing differential heave and torsion rotational motion, and then finally the use of a complete solid structure. I think you will find that other speakers later today will be telling you more about those sorts of problems. The mooring we haven't really talked about because we haven't got a lot to say yet; it's still a problem we are facing.

Sir Hermann Bondi (Department of Energy)

I would like to express a straight irritation that we know so little about the sea and the waves of the sea. Windmills have been there for very much longer and it is very irritating that at this stage, after oceanography has existed for a long time, we should still have such large margins on the power, on directional data, on periods. We even understand little of how perhaps the load factor might not be quite as low as indicated because of a measure of synchronisation between availability of power and demand for power.

M J Platts

The trouble with wave data is that it has been collected for designing ships; the sort of data you need for that is much simpler than the data that you need for predicting wave energy. For ship design you don't need to know about directionality, you don't need to know statistical correlation between what is happening off the North of Scotland and the South of Cornwall; all sorts of things we need to know for wave energy have not been needed before. The problem is that we need to collect a lot of data over a long period of time and the wave energy programme is chasing the wave data as fast as it can; inevitably it is going to be some time before we can answer those questions.

Dr G Owen (Heriot-Watt University)

I wonder if the speakers could talk about the problems of shipping lanes and also the difficulties in rafts coming adrift - how would you capture a unit in such a situation?

M J Platts

Taking your last question first, I am not too sure as yet how we would capture a unit. Obviously with large numbers you are going to get occasionally individual failures and breakaway; it is not easy at this early stage to imagine how one tackles such eminently practical problems – you sort out an emergency procedure from experience only. There is some
conflict with shipping lanes, but how that conflict will stand in 30 years' time, I am not too sure. I have had the suggestion put to me that the situation at sea is rather the equivalent now of the situation on land in this country at about the time of the closing of the commons. When the common land was divided up, rights of way, privacy and trespass, became far more organised and there were all sorts of areas of land which were then not open to the general public. As 50 mile limits or 200 mile limits become more delineated and better policed, the same sort of thing will begin to happen at sea; there will be distinct roads into ports and there will be very large areas of the sea which other ships should not be in and navigational aids will have improved very much purely for those reasons. Wave power in those sort of timescales will not look such a great hazard – it will still be a hazard, but it will be more for local ships and fishing. There will then be an interplay between the requirements of wave energy and the benefits as well as difficulties that it gives to the local shipping industry by the better weather window it gives behind itself.

D Ross (Journalist)
Mr Platts made it clear (if I have got his figures correctly) that 24 rafts could be produced a year using the facilities of two shipyards. Why, when the shipbuilding industry is absolutely collapsing in disaster, is he so modest in his claim on the shipyards. Why, when the shipbuilding industry is absolutely collapsing in disaster, is he so modest in his claim on the shipyards; and, if it is not indelicate, could Sir Christopher comment on it?

Sir Christopher Cockerell
I think you are getting into the realm of politics and I don't think we should be bothering our heads about these sorts of things – we have got plenty of real problems of an engineering and technical sort.

W Haley (Lawrence Allison)
Could you perhaps tell me what materials you are thinking of for the hinges as regards corrosion, bearing forces and the maintenance of frictionless surfaces?

R Comyns-Carr
We are aware of hinges that are being used under water, which are essentially bronze-based but using a solid lubricant deposited in the bearing material. This might be the line that we pursue. We have quite a good deal of latitude, in the design which we showed you, with regard to the size and stressing that we need to apply, so we haven't at the moment gone much further than just indicating a ballpark size. We visualize a size of about 0.5 to 0.7 m diameter.

J Falnes (Technical University of Norway)
How many tons of steel do you use in the raft construction if you construct it from steel? What is its volume in cubic metres?

M J Platts
The steel hull of the raft is 100 m front-to-back, 50 m wide and 8 m deep. The last design we did was 3380 tonnes of steel although I think we can bring that down quite some way. We have to ballast it to float at 3 m draft, giving 15000 cubic metres displaced volume. The concrete raft is a little bit heavier than that, about 18000 tonnes, so it floats near 4 m immersed.

C W Maynard (CEGB)
I suggest that the 25-year cycle for components is unrealistic as is the lead time mentioned of 25 to 30 years. Thirty years ago the CEGB's latest power station at Mefford had 30 MW sets. Our standard sets today are 860 MW. Nothing is so sure as that after ten years of development you will need to change the whole of your system; the raft building programme I would have thought would have to be very much greater than you suggested in your paper.

Sir Christopher Cockerell
Presumably the CEGB changes its devices partly because it uses fuel. In other words it is after efficiency; but if your fuel is free in the form of waves then there isn’t the same necessity to take out of service an obsolete design unless the maintenance has become too impossible.

M J Platts
I would like to comment on that as well. Obviously you would not expect to go on producing a static design for 25 to 30 years or for ever. There would obviously be a lot of development and change. The projections that we made were to get a feeling for the order of magnitude of the problem; the design we will have next year won’t be the same as we have got this year. In steel, that production programme of 300 rafts a year requires 20 to 25% of the UK’s annual steel production and a little more than the present steel throughput potential of UK shipbuilding yards. We have got a lot of improvement to make in the designs but you come up against the same problem whichever way round you do it. Any energy technology, if you pursue it at a reasonable scale, is going to take a slice of the national resource.

R T S Baker (Sheffield Polytechnic)
Mr Platts told us that there was a considerable time required before all the necessary information about the waves of the ocean could really be assembled. Could he say how long, and whether that was absolute or whether it was dependent on the amount of money put into the research programme?

M J Platts
It can obviously be speeded up to a certain extent by money. It’s not an absolute delay; it’s not as if we have no information for five years and then suddenly drown in it. We do have some information already, the sort of thing we are making our present predictions on, and the situation is one of steady improvement in width of understanding and in accuracy of data. You can improve that certainly by pouring more money in. There must be a time lag of say a year in order to build things and put them out there and get some data back. That accepted, if you build ten and put them out you are obviously going to get more information than if you put one buoy out and then move it to get information at another site. There is a fair amount of work being done now around the UK putting buoys out to get basic wave data but there is a development problem. In particular we need directional data; we need to know which direction the waves are coming from, and at one time there may be waves coming with the wind from one direction and swell still coming from another direction from a storm out in the Atlantic two days ago. That requires a much more sophisticated buoy; there is one in existence, and others are being developed, but it’s a very new technology and there is a limit to which even throwing money at it will speed it up.
THE DEVELOPMENT OF THE DUCK CONCEPT
S H Salter (University of Edinburgh)

matches the orbital motion of water particles in an
approaching wave while the displacements astern are very
small. No new waves are generated astern until the duck
moves through large angles but then the incident waves are
so large we do not mind losing some of the energy.

Figure 2 shows a model in our narrow tank at its working
attitude in calm water. Figure 3 is a time exposure of the
same model with waves. We have added some tracer fluid (a
neutrally buoyant mixture of carbon tetrachloride, xylene and
pigment) and you can see the orbital motion in front of the
model with very little movement behind. The broad band of
light left by the meniscus shows the envelope of the
approaching waves with a small standing wave ratio
indicating a little reflection. If you are good at hydrodynamics
you could tell a great deal about ducks from this picture.

Irregular wave tests

During the last year we have been testing models in the
narrow tank on mountings which can move in a controlled
way to represent the behaviour of compliant jointed
backbones. We have tested models in conditions which cover
the whole of the Station India scatter diagram. We have
measured angles, velocities, torques, the forces in heave and
surge and their long-term average sinking and mooring forces.
We have imposed various torque limits to the power take-off.
This gives a comprehensive data base which is available in our
4th Year Report. Perhaps I should show two examples.

Figure 4 shows the power output against RMS wave
amplitude for a range of energy periods and a fairly generous
amount of torque in the power take-off (2 meganewton
metres per metre). There is very little variation of output

Figure 1: The movement of the duck attempts to match the
movement of the water in front without making waves behind

Ducks evolved from simple, vertical flaps. What we wanted
was a flap which had a front but no back. The duck shape is a
stubby aerofoil section with a rear surface in the shape of a
cylinder coaxial with the centre of rotation. The idea (shown in
Figure 1) is that the front surface should move in a way which

Figure 2: A 1/100th scale model duck in calm water

Figure 3: A time exposure of the same model with tracing
fluid showing orbital motion

Figure 4: Output power against wave height for various
energy periods with a high torque limit of 2 MN/m/m
power with energy period because, for this duck design, the fall in efficiency at longer waves is balanced by the larger amount of energy in them. At low amplitudes the output power follows the square law of the input power. But at an RMS amplitude of about 1 m, the curves become linear and, at about 2.5 m RMS, they begin to level off at about 200 megawatts per kilometre. Suppose now that we halve the torque limit. The results are shown in Figure 5. Initially the curves are almost the same but they flatten off at 100 megawatts per kilometre. Torque is expensive. We have to make a careful decision on how much we have to provide.

A second example of the data base is given in Figure 6 which shows the mooring force against RMS wave height. We get a mooring force of 20 kilonewtons per metre even in small seas but it stays level and perhaps even falls off at higher wave amplitude. We have had one negative value for very steep waves. The reason for this is that when the duck goes over backwards it generates a new wave behind and dumps the unwanted momentum into the sea. This is a particularly desirable feature.

We can summarise the results of the experiments in Figure 7. We take the results, rescale them for different duck diameters and apply them to various wave climates. We get power output as a function of duck diameter and torque limit. If we knew the costs of duck diameter and torque, we could decide which combination would give the best value for money for any particular wave climate. We can see that there is only a small amount to be gained by going from 10 m to 15 m and that, while 1 meganewton metre per metre of torque is good, we could manage quite well with only one third, if it turned out to be too expensive.

Power take-off

We have to resolve a number of conflicting problems. According to the simplest theory, ducks ought to feel a torque which is proportional to their angular velocity, and indeed this is the easiest power take-off scheme to analyse. But this is in direct conflict with the mechanical desirability of pumping into a constant pressure pipe network. Furthermore, someone is bound to think of clever ideas for a phase shift or time lag which will need torque which is an even more complicated and perhaps non-linear function of velocity and other parameters.

The second conflict is that we would like to have all the pumps well isolated from one another so that broken fragments from one do not destroy others, but we would like to concentrate the power from many.

The third is that while the most attractive fluid to pump is oil,
It is expensive, troublesome if spilt and hard to send through long pipes. Water would be much cheaper. Perhaps we can design a hybrid system which starts off with isolated oil and then changes to water.

To give you an idea of the difficulties, Figure 8 shows a wave record, the corresponding velocity-proportional torque with and without a limit, and the terribly spiky power signals. We ought to try to average lots of uncorrelated versions of this if we want a smooth processed output.

Pump drives

It has not turned out to be easy to drive a pump from the relative motion of duck and backbone. We have found some good ways not to do it. I will show you one or two of them.

Figure 9 shows a rather large gear round the inside of a duck driving a couple of rotary pumps. The problem is that the location between duck and backbone will not be very precise. We should expect geometrical errors of ±100 mm or more. We must think about Landrovers on country tracks rather than lathe spindles. If any gear design is to stand a chance it must have a following mechanism to keep it properly in mesh. I believe that it will be difficult to make the gear idea work.

Can we use tension? Our torques represent only about 14 tonnes of tangential force for every metre width of duck. I have a piece of material here which is not much thicker than my tie. It has a label which says it can take 20 tonnes although it does not say for how long and with how much rubbing. We cannot use friction belts in water but suppose we wrapped a belt round a pump body (as shown in Figure 10) and then took it right round the backbone to a similar pump. With this scheme, as the duck moves the tapes are wound off the pumps alternately. They work in pure tension and are very tolerant of duck location. But the problem is that we have to recoil them for the next working stroke, so they have to have little pony motors and they only work for half the cycle.

We can solve the rewinding problem if we use toothed belts arranged as in Figure 11. Belts are available with teeth on both sides and the people who make them say that we can get half a meganewton metre of torque per metre width of duck without stretching present technology.

I am happy about the belts. The problem arises with radial loads suffered by the pump bearings. It is much better to deal with a pure torque than with force at the end of a radius which has to find a reaction.

All these designs use pumps in water. Pumps are available now with shaft seals which are good enough for them to work in seawater. This seal is the barrier between the seawater, with all its horrible marine growths, salt and corrosion, and the electricity. Where we draw this frontier and how well we defend it will govern success or failure.

My last example of a power take-off mechanism grew out of a meeting with Professor Eric Laithwaite of Imperial College. I had been beating my head against a wall trying to think of a way to make very low speed electrical generators. I was getting nowhere and so I decided to go and talk to him. He
will also remember the equations relating output torque to spin speed \( \Omega \), disc inertia \( J \) and input angular velocity \( \dot{\theta} \):

\[
T = J\Omega\dot{\theta}
\]

and will have no difficulty in working out the way to load pumps acting between the gyro duck frame and the duck casing so that the duck feels the right damping coefficient. In round figures, we need gyro discs weighing about 50 tons, spinning at 1,000 rpm with a diameter as big as can be fitted inside the duck. We can exercise a good deal of control over the design by choosing the moment of inertia, the speed of spin and the damping coefficient on the gimbals. In case anyone thinks that this scheme is far-fetched and that we could not work gyros of this size at sea, perhaps some of the marine engineers present remember the Italian liner ‘Conte di Savoia’ which used gyros for stabilisation in the 1930s. Three gyros, each weighing 100 tons (double the weight I have mentioned) were run at 950 rpm. I understand the method was quite successful\(^\text{[1,2]}\).

Inside the duck we build two large gyros arranged to spin in opposite directions. Their axes are perpendicular to the duck’s axis of nod as shown in Figure 12. I am sure that you will all instantly know how exactly what will happen to the gyro gimbals when the duck nods! They will precess about the axis which is perpendicular to both the axes of spin and nod. You

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"Figure 10: The tape scheme for power take-off. Pumps can only work for half the time"

"Figure 11: The toothed-belt power take-off"

"Figure 12: Plan view of the gyro scheme"

There are several attractive features of the gyro idea. We no longer need any torsional strength in the backbone. Secondly, we can take the opportunity of using the gyro spin for energy storage. If you look at values for \( J\Omega^2 \) you will find that at full speed each gyro stores about three-quarters of a megawatt hour so that very little speed variation can provide the few minutes of storage necessary for wave power. But the most attractive feature is that we have a completely opaque barrier between ourselves and the salt water. The gyros do not know that they are at sea. I do not need to know about marine biology and corrosion to make them work. If they will work in my laboratory, then I can be confident that they will work at sea.

The problem is that we have got to put some large forces through bearings spinning at 1,000 rpm or more. Other wave power bearings have enormous forces on them but at slower speeds. The bearing problem is serious. But it is a precisely definable problem. (Since the Conference I have been advised that for hydrodynamically lubricated plain bearings, high speeds of rotation are a virtue and that the low speed frame bearings may be more difficult than the gyro ones.)
Figure 13: The Pitch-Heave-Surge Rig

Figure 14: A time exposure of a model on the Pitch-Heave-Surge Rig

Figure 15: Efficiency contours for various heave and surge compliances at waves eight times the duck diameter
Backbone compliance

I would like to describe some work on backbone compliance. While our very first models were mounted on a fixed axis, this is clearly impractical at sea. We plan to get our reference by spanning a large number of wave crests. This gives us terrible bending moment problems and possibly even a rigidity problem, but it has several advantages too. We can share mooring forces along the length and distribute power up and down the string. We do not have to worry about side-to-side collisions. It is obviously important to find out what happens when the backbone bends.

We have been working with the apparatus shown in Figure 13 which we call the pitch-heave-surge rig. For ducks whose backbones have no external appendages, pitch can be modelled electronically using conventional analogue computing techniques. The heave and surge motions are transmitted to two horizontal spindles. Heave is constrained by a straight-line linkage but surge is a short arc of a circle.

Friction is reduced to very low levels by the use of leaf springs, point joints and ball-races. Each spindle can have its inertia increased by the addition of pairs of weights. Its stiffness can be controlled by the length and thickness of torsion springs which are contained in rotatable housings used for adjusting axis depth and surge position. We also provide torque motors which can modify stiffness, damping and inertia electronically as well as putting force command signals on to the duck's backbone. A set of strain gauge transducers measure heave and surge forces close to the duck.

There are two channels for measuring backbone movement. Our usual microammeter transducers measure velocity, which can be integrated to give a short-term position signal, but there are also position transducers made from strain gauges bonded to leaf springs in the microammeter drive linkage.

The rig is by no means a perfect simulation of a backbone and there is some question about the values of stiffness, inertia and damping used to restrain the spindles. But it does show

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Figure 16: Efficiency contours for various heave and surge compliances at waves fifteen times the duck diameter

| total surge inertia: 374 tonnes/m | nod damping: 7.7 MN/rad/s/m |
| total heave inertia: 542 tonnes/m |                               |

- 22 -
that ducks can work on a moving axis and David Evans has used it to show that Ogilvie’s cylinder can absorb power from waves. It allows us to measure some useful coefficients for theoreticians and is probably the most realistic way of using a narrow tank. Figure 14 shows a duck at work on the rig with tracer fluid and the familiar ratio of envelopes. The wave length is 15 duck diameters.

We have carried out a systematic investigation of mounting compliance. I would like to show you the sort of results we have obtained. Figure 15 shows what happens at a short wave length of only eight times the duck diameter. We are looking at a map of compliance country. As we move east we are increasing surge compliance and as we move north we increase heave compliance. Each position in the map defines a particular sort of mounting. The bottom left-hand corner has zero compliance in both directions and denotes a locked axis. An infinite distance away to the top right-hand would represent a free duck. Note that the heave compliance scale is ten times greater than the surge one. The contours of the map are lines of constant efficiency. For this frequency, as we increase surge compliance, the performance shows a steady fall. But as we increase heave compliance, we enter a low ‘death valley’ where the efficiency falls to below 20%. But if heave compliance is further increased, we can reach a second high performance region with results as good as for a fixed heave axis.

If we do the same experiments at lower frequencies, we get the results shown in Figure 16 which are for waves 15.6 times longer than the duck diameter. The high mountains have moved towards the more compliant direction and a good deal of surge compliance is actually desirable.

We started these experiments after discussions with David Evans and we believe that the results can be explained if we think of the backs of our ducks as behaving like his cylinder. We are generating a wave behind the model which is the inverse of the one that has sneaked underneath. The helpful thing about it is that we can expect that at sea the high frequency waves with short wave lengths will make short intercepts along the backbone and think that it is rigid, whereas the long waves will think that it is compliant. The backbone can appear to have a different compliance at each frequency in nearly the way we would choose.

I would like to show you how the performance curves have changed as the project has progressed. Figure 17 is a set of historical curves plotted against wave-length-to-diameter ratio. We began with the 1974 ‘church steeple’ of 90% efficiency at waves only four duck diameters long. But after we got some money from the Department of Industry, we were able to push the efficiency curves further towards the longer wave lengths without too great a fall. In 1975 we found out how to use reactive power take-off and in 1976 we discovered ways of achieving the same results with high centres of gravity and plain power take-off. The crosses show the results for 1978. It is not legitimate to draw a curve through them because they were made on models with different mounting compliance. We shall need to do wide tank tests in irregular waves to confirm these. But you can see that if we should get figures of 70 and 80% at wave lengths about twenty times the duck diameter. To match a 10 second Atlantic swell we might be able to use ducks only 7 m in diameter. (Since the Conference I have heard about some work by a student at MIT who has achieved 187% efficiency with ducks by exploiting point absorber effects[31].)

Freak waves

As well as trying to be efficient in calm conditions we have to worry about survival in rough ones. We have been looking at duck behaviour in some spectacularly steep waves. Figure 18 shows the record of the steepest wave we can make in the narrow tank. It consists of 40 spectral components with their phases fiddled so that the crests all coincide at the same place. We believe that repeatability for tank experiments is just as important as purity is for chemistry. Figure 18 is in fact a double take of two wave records superimposed.

The computer which generates these waves can also trigger a camera shutter and electronic flash. Figure 19 shows a time series of photographs with an interval equivalent to one second at full scale. Figure 20 shows the same series of the wave hitting a duck. It is interesting to compare them with Figure 21 which is a theoretical prediction made by Ned Cokelet from IOS, Wormley[4]. He did this before we had taken any photographs. I think that the accuracy of his prediction is remarkable. I believe that he had to solve hundreds of simultaneous equations. At full scale this would represent a wave with a crest about 20 m above mean sea level and a trough about 10 m below and water would fall vertically from the crest at 20 to 30 m per second. Ducks will recover on their own from capsize after this sort of wave if they have humps on their backs and the right arrangement of ballast.

Figure 22 shows three closer views of the model taken at the same time from the start of the wave sequence but with a small foreign body included to show that the photographs are not duplicates. The duck angles and the water crossing agree well but we cannot promise to get every fleck of foam in the
right place every time!

We can also record the forces during the passage of the wave. Figure 23 is a sample of the results. The top record is what the wave would have been like without a duck. The second line is a time track which lets us relate the force measurements to the photographs. This is followed by the surge force, which looks quite like the inverse of the wave record, and the heave force, which shows downward tendencies during both crest and trough. A freely floating model in the wide tank would sink so as to get out of harm's way. We can also combine the two force records to show their resultant. The mean downward forces are about an order of magnitude greater than the mooring forces and this is a good thing. The biggest forces do not always happen at the most spectacular part of the sequence.

We have made this sort of record with the duck placed in various positions fore and aft of the breaking point, with its axes free and locked, with high, intermediate and zero power take-off torques, and we have assembled an array of graphs like this. We find few cases of slamming spikes because so often the duck is submerged and protected by a blanket of water. If a duck on a fixed axis had to survive the extreme waves, it would have to take loads of about 140 tons/metre width. But if we can let the ducks move when things get too rough, then we should be able to get the forces down to less than 70 tons per metre.

In Figure 24 we have replotted the force measurements in polar form. The dots are instantaneous force vectors one eighth of a second apart at full scale. The numbered squares
relate to the times in the force record and photographs. It is interesting to see that there is practically nothing in the top right-hand quadrant. This means that we should not use an even distribution of tyres or bearing pads. We should space them so that they get a more even duty.

I would like to show you how we are planning to support these loads. Figure 25 shows part of the duck and backbone separated by tyres rather like the rollers of a ball bearing. The cage of the 'bearing' will run at half speed. Its radial thickness will be chosen so that when the tyres collapse we get a plain bearing between the cage links and a cupro-nickel shim bonded to the inside of the duck and the outside of the backbone. The surfaces of the links are covered with a rubber bearing material which takes over when the tyres have had enough. The tyres give a low rolling resistance in calm conditions and in rough conditions we can afford the frictional losses of the plain bearings.
The wide tank

Our new wide tank was ready at the end of 1977 and was designed especially for the project. It seems that wave power demands much more from tanks than is needed for ship towing. The tank is 27 m x 11 m and has 89 wave-makers. They can absorb reflections from models and this makes wave conditions much more stable. Figure 26 shows a view looking down on the wave-makers from behind. They are made as light as possible and driven by a wire from a printed armature motor. If they are all driven together in phase we get simple long-crested waves as in Figure 27. But if we introduce a progressive phase shift to the command signal sent to each wave-maker, we get oblique waves as shown in Figure 28. And if we add a second component to the drive signal we get a second front moving in the opposite direction as in Figure 29. This is the simplest possible short-crested sea.

The wave front is the building brick of a sea state. It is specified by four numbers:
1. The wave frequency
2. The wave amplitude
3. The phase difference between adjacent wave-makers
4. The starting phase.

If you combine a number of fronts, you can produce a spectrum with control of directional spread. The sea state shown in Figure 30 has a Pierson-Moskowitz spectrum with an amplitude at the top of the scatter diagram and the Mitsuyasu angular spread. We have a computer program which allows us to compose our own sea states or generate various multiples of the Mitsuyasu spread or cosine to any power.

Even though the wave-makers are in a straight line we can make waves which are circular. Figure 31 is the pattern we call the bull's eye. It is an excellent way to generate very steep monochromatic waves. There is no doubt that plunging breakers can occur in deep water even with regular waves if energy is brought in from the sides. Figure 32 shows a section through the bull's eye.

If the starting phases of the wave fronts are chosen so that they combine at a particular place and time, we get a freak wave which has devastating effects on a model trawler, as shown in Figure 33.

During 1979 we will be concentrating on the construction of a free-floating 1/100th scale duck string and the development of the critical parts for full-scale power take-off mechanism.
References


DISCUSSION

Dr P K Probert (Nature Conservancy Council)
I wondered what the current thinking was on moored versus unmoored designs. In one of your earlier papers you envisaged an unmoored string of ducks that would be powered back into the Atlantic: what's the current situation?

S H Salter
Yes, we started off thinking about free-range ducks, making hydrogen or ammonia or something; then people said "Oh no, mooring is no problem at all, anyone can moor anything – it's 10p a tonne-metre", so we said "as electricity is nicer than other things, let's try and moor them". Maybe that was wrong. We are learning now that we are asking for mooring conditions, and particularly mooring lifetimes, that are not available at present. Perhaps if we have got much more wave energy out to sea, and we have got a real problem on the mooring, then we should bring back the free-range duck – or free range other devices I should say, I don't want to be personal about it.

Prof D T Swift-Hook (CEGB)
Could you say whether you thought there was any chance of seeing these rather weird confluences of waves coming so that you could submerge by using things like radar, asdic, sonar, or any of the fairly straightforward techniques?

S H Salter
I don't think so; I think you could say "there is a bad storm coming, let's submerge", but these waves can come out of a fairly calm sea. In our freak waves you don't see something happening; it's just that one appears to grow. We wouldn't have long enough to sink the whole string. We might need about a quarter hour to get it down, and we may only have about 30 seconds' or a minute's notice of something coming at us. Also, we are then relying for survival on the reliability of this radar system: that's trusting in the radar guys tremendously, and we might have to have a lot of diversity in that system. If we can keep submerging as an emergency thing, if we can make something take the peak conditions at the surface and then use submergence as a last resort, that's the approach I go for; but we are going to see how easy it is in the wide rank, and then we shall tell you.
THE LOCH NESS TRIALS OF THE DUCK
Dr N W Bellamy (SEA/Lanchester Polytechnic, Coventry)

Lanchester Polytechnic is in Coventry and Coventry is in the Midlands, the exact centre of the country and therefore we are as far away from waves as we can get. Three years ago we were inspired by Stephen Salter’s work and started looking into wave power technology in the shape of a duck. During the early work we felt that having no equipment and no money we had to look for the cheapest waves, and the cheapest waves were on our local reservoir which we discovered was about 1/50th scale of what the wave fields are in the Atlantic.

The first thing was to test the total concept of the duck device in the natural wave environment, and in particular whether the spine principle would help the ducks to work by balancing the forces and torques along a spine. The early work resulted in what we call the Draycote model which, at 1/50th scale, was 6 m long and built of plastic and fibre glass. Power absorption was achieved by water pumps inside each duck which fed a common main and pumped water ashore. When this device was built and put into the water, nobody quite knew whether it would work, but after one day at Draycote and 10,000 waves later everybody was convinced that the spine principle was sound. We then moved on and lengthened the device because we thought that a spine twice as long would be twice as stable and therefore more efficient. We pumped the water ashore and produced jets of water of which we measured the pressure and quantity. It was very surprising that we seemed to be absorbing from the waves up to 50% of the available energy, which was very encouraging for a rather crude model. Unfortunately of course the power take-off was only 50% efficient so only 25% came ashore. It illustrated, as in Figure 1, the phase differences between each duck which give the balancing action in the form of heave, surge and torque. The attenuation of the waves going through the device could be seen as well as some sign of mis-match causing reflection ripples at the front.

After the Draycote tests we looked around for a site where we could build a larger model which was nearer to the engineering scale and found that Loch Ness (see Figure 2) was the largest natural wave-tank in the country. It is 35 km long and is orientated towards the south west where the prevailing wind is supposed to come from. It is fresh water and hence avoids marine fouling, tides and currents. We investigated the wave climate of Loch Ness and found it to be about 1/10th scale of the North Atlantic. It is situated in a very beautiful part of the country and the test site was chosen near the little village of Dores which has a very attractive pub. The beach behind the test site is very good at absorbing waves, and has done so for many millions of years.

The first thing was to build a spine and although the Loch Ness scale was 1/10th of the North Atlantic, which is only four times bigger than the original Draycote model, the volume and weight at four times cubed is rather a large figure. The spine was nearly 1 m in diameter, 50 m long and can be seen in Figure 3 coming out for the first time from an old factory on the banks of Loch Ness where it was built. This was instrumented along its length for bending moment and dynamic performance and was put into the water during May 1977.

Eventually, after a long period of calm illustrated in Figure 4, the waves did come and we were able to take all the results required. To measure the waves a wave tower, shown in Figure 5, set in 18 m of water, recorded the wave height in a 7-point array from which we hoped not only to measure the height for the wave at a point, but also get some information on the directional spectra which is of the utmost importance.
in wave analysis. This has been improved upon since the first model and has given some very valuable information. Unfortunately our knowledge of the waves at Loch Ness far exceeds the knowledge of the waves in the Atlantic so it is very difficult to compare the two. Loch Ness wave climate was very predictable; mathematicians will know a formula called the JONSWAP formula which means you can predict the waves at a particular site as illustrated. Figure 6 shows the measurements and the predictions which agree extremely well with the Fitzroy data from the north of Scotland. One difficulty was that we didn’t know when the scaled 50-year wave would come and how many times a year.

The spine was well instrumented with cables to land and a computer to record and analyse the results. Figure 7 shows the device and its mooring, indicating the instrumentation of the structural heave and surge strains and the dynamic accelerations. The problem was that the amount of information that came ashore was overwhelming; we had 30,000 waves a day and a lot of days of waves. Our tests covered 6-minute periods and each test gave one point on the heave and surge strain diagrams. These are the basic results that came out of the tests. The important point about the spine is that in order to survive it must resist a bending moment which will break its back. Figure 8 shows the bending moments in terms of RMS strain as seen at the centre of the pipe in terms of significant wave height. You will notice that the surge strain due to horizontal forces, is roughly twice as much as the heave strain due to vertical forces. The first part of the curve is straight and predictable and mathematicians can put formulae to it and give you answers. Unfortunately the mathematicians are in difficulty as soon as you get to the knee of the curve, when it becomes non-linear. This, of course, is very important since if these bending moments had increased linearly all the way, the spine principle would be in jeopardy but fortunately after the knee of the curves the strain is limiting. The reason for this is that for small waves the device is relatively stable and takes all the forces as bending moments along its length, but as soon as the waves get bigger the crests get longer and the whole device has body movement which limits the apparent wave.
height seen by the spine. This levelling-off is very encouraging for survival – in fact the worst measurements were taken not in survival conditions but near the maximum of the operational conditions. The heave strain is not quite the same shape but exhibits a similar type of characteristic. We measure the bending moment along the spine in terms of strain again and obviously the centre became the most important area where we can see the maximum bending moment was exerted at the centre where you expect it, but we had to measure its distribution in case there were any other modes of oscillation, other than the fundamental. Note that the surge is roughly twice as much as the heave.

Everybody is interested in the mooring forces, and here again the results were very encouraging. The mean mooring forces due to radiation pressure on the device (shown in Figure 9) proved to be linear and followed the predictions according to formula up to a certain level, but as soon as body movements became apparent and waves were generated behind by the body the cancellation forces took place and the mooring forces levelled off in a self-limiting manner.

The problem when one has a lot of data is to concentrate that data onto one sheet of paper in order to see what it all means. The design curves for spine devices in Figure 10 show the costs of a particular length of spine, in terms of spine diameter and equivalent wall thickness. From these curves we can decide what can be built, what will float, and how much weight we can devote to equipment. Obviously the cost is the dominant parameter in this curve.

After the spine tests we went back to constructing a string of 20 ducks onto our basic spine. We filmed the construction and assembly of the duck string and its operation.

Figure 11 shows half the duck string, with a number of cylinders mounted on bearings on the spine, and with each driving a toothed belt coupled to a toothed pulley and driving a hydraulic pump. The hydraulic pumps had valves to rectify the nodding action of the ducks and the hydraulic power was pumped into common mains down the spine to the central hydraulic power unit. The polystyrene buoyancy modules hold the device at the correct depth in the water. The device was built in two halves because it was too difficult to transport as one 50 m length. The assembly of each half took 2 to 3 weeks, with the electronic instrumentation taking about 8 weeks. 80 signals were brought ashore by cable and recorded.

To launch the device required a rather large crane (see Figure 12) – the whole device weighed 25 tonnes and, being 50 m long, was a very difficult shape to pick up. One can see the mooring points along the device at the $1/4$ and $3/4$ points for connection to a leading buoy and to a one-point anchor system in the bed of the Loch. Figure 13 shows the device being picked off its sleepers – in fact the largest strain induced in the device was when it was actually being picked up by the crane at one end, not by the waves. The duck string was lowered down the frontage of the hydro-electric power station at Foyers. One of the problems of launching a device of this size is the availability of adequate weather windows since the conditions at Loch Ness can change within half an hour making weather forecasting very unreliable. It settled down eventually to about 5% reserve buoyancy; the spine was submerged with only steel work showing above the surface.
After towing to the Dores Bay test site in December 1977 tests were carried out for 3 months in the worst winter for 30 years. The weather window during testing was about 10%; that is the chance of working on the device for maintenance and experimental reasons.

Eventually, after a lot of teething troubles and modifications, the device was put back in the water again in September 1978. Figures 14 and 15 show various views of the device operating with the ducks nodding as they produced power. Figure 16 is a helicopter shot showing the diffraction of the waves around the device, an effect of major importance to wave power workers. We filmed the device from the bank, operating during storm conditions where the duck and spine response to waves was very dynamic. Waves up to 4 m high with RMS values of 1.65 m have been encountered.
For small waves, the efficiency was surprisingly high but this fell off with increasing wave height although power output levels remained reasonably constant. Experience is now being gained in handling and controlling this wave power station. Indications are that increased efficiency and power output capacity will be achieved by angling the spine about 20° to the wave front.

What have we learnt at Loch Ness over the last year? First, we have run a 1/10th scale wave power station. It is only 4 times bigger in scale than the previous Draycote device which we really regard as a toy, but it is still nearer the realm of heavy engineering. It certainly gives cause for worry when one thinks of increasing the scale by a factor of 10. Tackling engineering problems at 1/10th scale is difficult; to go 10 times bigger where the strength of materials does not increase proportionally is a formidable problem. Even so, the device does work, it does produce power and it demonstrates that you can gain energy at relatively high efficiency. It also demonstrates that survival is the main problem and that reliability is all-important. We regard this device and the Loch Ness trials as a major evolutionary step in wave power. We think we have got a long way to go and our next thoughts are to reduce the scale of materials involved by an order of 5 and, if possible, to reduce the complexity by an order of 5. What we must finish up with is a very simple structure which will survive and not cost too much.

**DISCUSSION**

G H Taylor (Redpath Dorman Long)
In the previous lecture by Wavepower Ltd. they did discuss very briefly the choice of materials. Seeing your models, made in steel, have you any feelings on how this will develop? I notice your figure of £1000/ton as well, I hope this is not going to be the yardstick for full-scale production?

Dr N W Bellamy
We have only been concerned with a 1/10th scale here but we have carried out full scale reference designs, and we feel that as wave power develops to full scale the first ones will be made in steel. We can chop and change steel and vary designs very easily; but when successful we will convert the steel prototypes into concrete wherever possible.

R T S Baker (Sheffield Polytechnic)
Dr Bellamy said that there was a long way to go but I wonder whether his experiments take us any nearer to an estimate of what is involved in time and money before there is something in the sea. Is there even an approximate further idea of when that will be?

Dr N W Bellamy
I don’t think it’s for me to answer this question. We started having doubts about the cost and the materials demand of wave power as soon as we started to build the Loch Ness device. What we found is that when you do a paperwork exercise you can fudge over a few issues, but when you start to build something and order the equipment and be confident that it will survive, the approach has to be different. We have to take everything into account including what it is going to cost. It disciplines the mind tremendously and in so doing makes us concentrate on the problems ahead of us at the full-scale stage. In particular, how does one make a device which is reliable enough to work off the Hebrides (which they tell me are much worse than Loch Ness) for three years unattended? I believe it is a matter of sheer hard work and aiming towards the end. I believe it all will become easier as we get over the initial hurdles.

P Bullman (Engineering Design Partnership)
I would like to ask a little more about the spine. The first question is does the spine undergo a slow net rotation, on a sort of statistical average of the duck movement, and if not how is this prevented?

Dr N W Bellamy
The spine is ballasted off-centre and hence has a strong preference to remain vertical. It therefore tends to orientate itself vertically even in the presence of net positive torque or a net negative torque on the device. If the ducks cause it to rotate it stores energy due to rotation against the offset buoyancy and, when it comes back, it dissipates that energy into the ducks themselves.

S H Salter (Edinburgh University)
The first point is that Norman’s only got one length of spine to work with at a time, and he can’t change it very easily. But in our tank we’ve put in a long plastic drainpipe; we get exactly his curve up to the first little bit and then we find the bending moment falls as you get in towards the middle. So we believe (and we have got to find a way of making it) that infinity is the best length for a duck string. What we are trying to do at the moment is to reduce the duty that this spine has got to have. We started off thinking that it had to be very rigid in heave and surge in torsion. We now find that we can let the heave go completely loose, and if the gyros work you don’t need any torsion. A way to get a joint that will work in the surge direction is to have a single movement at each one and to control the movement with some rams or a composite rubber buckling strut. It may be possible to build ourselves a composite material of a kind which isn’t actually available. The only material that I know of that can do a continuously rigid backbone is bamboo. It has the right modulus and strain capability, but we haven’t got enough bamboo to make our duck backbones.

J Barry (Bertlin & Partners)
I think practical trials make one learn a lot and I wondered if there were any problems with the moorings during the trials.

Dr N W Bellamy
When you have to take the responsibility for such trials you find the biggest anchor and the thickest chain that you can lay
your hands on and lay them in Loch Ness. Our anchor weighed $1 \frac{1}{2}$ tons and the chain was tested to 30 tons. Later we found that probably one or two strong men with good compliant arms could actually hold the device in any conditions. In fact we had to change the transducers to measure the small anchor mooring forces that we came across. We really over-designed the mooring system by a factor of 30 which rather upset the compliance. Although we did expect to have small mooring forces our first wish was to survive and that is what the mooring was designed for.

T P Higgins (Lockheed-California Co.)
Did you make any measurements during your Loch Ness trials of the power output? If so, are you able to make any extrapolations then to a full-scale system?

Dr N W Bellamy
Yes, during the last seven weeks we have been doing serious measurements of power. It is much more complicated than it first appears. We have got about 60 points now on our efficiency graph; that is a mean point for each test. The efficiency varies considerably according to damping, wave climate and alignment. The best measurements to date show an efficiency of 46.9%; that is the overall efficiency of transfer from wave to hydraulic power. This is encouraging since pump, bearing and drive losses are estimated as 50%. We expect that at device angles of $15^\circ$ to $20^\circ$ the efficiencies will increase considerably because we get apparent shortening of the crest lengths, which gives much more stability to the device.

D M Sharp (British Ropes Ltd)
In your illustration of mooring forces (Figure 9) was the period of the mooring tension a function of the wave period?

Dr N W Bellamy
Yes, there are many responses of the mooring system. There were the natural sort of surges related to each individual wave. There was also the effect of wave grouping causing the device to surge over long periods of $\frac{1}{2}$ minute or more. Added to this the device swings about its mean anchoring position over about a 5 minute period.

Dr T Carstens (River and Harbour Laboratory, Norway)
I am curious about Loch Ness as a wave tank. What have you learnt about, say, the directionality of the waves in the lake?

Dr N W Bellamy
Although we have got the recordings of the directionality from the wave mast these haven’t been analysed by the latest computer method. There has been a lot of difficulty with the Loch Ness trials in getting the right type of measurement device to measure the wave directional spectrum and the right type of computer analysis to process this data. You can expect Loch Ness to be very directional because it is a long thin reservoir, but of course it does have quite a few variations. For instance, the beginning of a storm we get very steep waves coming from all kinds of directions; at the end of a storm there is a tremendous swell.

I L McLeod (Howard Doris Ltd.)
You mentioned that the full size structure would appear to be 500 m long and 10 m in diameter. How many of these structures do you envisage and what rate of construction would be necessary?

Dr N W Bellamy
My answer is a lot of structures, and a long time to build them. This is the point made by Jim Platts earlier in his careful analysis of the production times for rafts and numbers of structures required. We haven’t done this particular analysis for the Salter duck device.

M Gauthier (CNEXO, France)
I understand you adjust the resistant torque between the ducks and the spine according to the sea conditions. How do you intend to adjust that resistant torque on a full scale system?

Dr N W Bellamy
Yes, there is an art in deriving the correct torque to apply to each duck, and this is a very difficult problem that we have been working on for some time. The Loch Ness device takes the easy way out and feeds all the duck output hydraulic fluid into a controlled constant pressure line, and so in effect you have a constant torque load which still works remarkably well. Stephen Salter has shown that if you make it velocity-proportional torque you can get much higher efficiencies but, with hydraulic systems it is extremely difficult to achieve this. We have not yet solved the problem. One method is to use a swashplate pump but this incurs losses and design complications. There are many ideas to solve this problem but we have not yet had the time to explore them all.
We have been working in the field of wave power at NEL for about three years now and I intend to describe what we have done during that time and what we have learnt. Figure 1 shows the earliest model that we worked with in the wave tank. It's a perspex model consisting of an inverted box which is open at the bottom, and closed at the top; in the top there is a brass orifice. The incoming waves induce the column of water within the box to oscillate, and this in turn induces an oscillating air flow through the orifice. We measure the elevation or displacement of the surface within the chamber and the pressure of the air in the chamber. In that way we can get the pressure/volume diagram, which is visible on the oscilloscope in Figure 1; it is a measure of the energy that is being extracted by the device. Such devices are called oscillating water columns and our attention has been confined exclusively to them. Figure 2 shows more clearly what is going on.

Our investigations have been made using two-dimensional models, both the physical model in the narrow tank and also a numerical model. It has been very useful to us to have both these tools available to allow us to investigate the problem; they complement each other rather nicely. The mathematical or numerical model gives us information about the details of what is going on which would be difficult to extract from measurements in a wave tank; the physical model tells us what happens in regimes where the assumptions on which the numerical model is based are no longer valid. It's a potential flow model and embraces for example eddy formation.

When amplitudes of response get very large the linearity assumptions break down, so it has been very useful to have both tools available. In both cases we are able to identify the magnitudes of the incident waves, the reflected waves and the transmitted waves and carry out an energy balance: that again helps give confidence in the results that we get. Figure 2 represents the very earliest models that we worked with. The first lesson we learned was obvious: that if we made the back plate deeper than the front plate it reduced the magnitude of the transmitted wave. We also learned that the maximum rate of extraction occurred when the column's natural frequency in heave corresponded with the frequency of the wave exciting it. It is a tuned system and there is obviously an optimum size of the orifice, an optimum level of damping imposed upon the column. There is a strong analogy between this and an aerial: if it is tuned and the impedances are properly matched then it will work so much the better.

As a result of this work we have come to the conclusion that Figure 3 displays something like the best geometry for a two-dimensional water column of the type we have been looking at. It's asymmetric, equivalent to having a back plate as I mentioned before, with generous radii at the aperture to discourage eddy shedding. We also have the mouth of the column pointing forwards rather than downwards, which improves the coupling between the column and the waves — or more precisely, it increases the added damping of the column. As most of you know, with a spring-mass resonant system such as this, if we can get the damping ratio up, raise the damping forces relative to the inertia and stiffness forces, then we get a good bandwidth. In fact there is an optimum value for the aperture of the device: if it is closed up too much, by raising the bottom plate, then it starts to throttle the column, equivalent to putting up the mass term. The damping ratio starts to deteriorate if this goes too far, and the aperture in Figure 3 is just about right; the differences between a well-proportioned column and just any old column are appreciable, so it's worth trying to do it right.

The top solid curve in Figure 4 refers to the column in Figure 3. The solid curves are derived from measurements in the narrow tank. The dotted curve is included for interest, and gives a comparison with the numerical model; it is very good in the case of the uppermost arrangement which has good
radii, but the comparison would be less good in the lower two cases which just have sharp plates. You can see that in the lower curves the bandwidth is narrowed substantially and the peak is reduced because of eddy formation. The lowest curve is for the most simple column of all, with an even narrower band and much lower efficiency; it's quite well known that a symmetrical arrangement could never exceed 50% efficiency. The period axis is drawn to scale from zero. You can see looking at the proportions that we are covering a band of about an octave with the fixed column, which is adequate for wave energy applications. There is no real incentive to get a broader bandwidth than is possible with that arrangement.

We have also looked at three-dimensional axisymmetric water columns. Figure 5 is a photograph of one of the models we have used, a perspex tube; again we tried to do something about the eddy formation so there is a fairing at the entrance and exit. It's convenient to define a capture ratio for three-dimensional devices like that. For the purely two-dimensional, the idea of efficiency comes naturally and the definition is self-evident; but in three dimensions we need another definition. Capture ratio is the ratio of the energy extracted by the device to the energy contained in a length of wave crest equal to the diameter of the device. It is an arbitrary definition, but it is the one that we have been using. There has been a lot of interesting theoretical work done to predict the performance of such arrangements.

We are attributing the curve in Figure 6 to Dr David Evans who will be speaking later in the conference. The curve is based on linear theory and part of it indicates the potential attraction, the reason why so many of us have been interested in point absorbers: we can get capture ratios greater than 1. But it is in the very region where the amplification is greatest, that the assumptions of linear theory are most questionable. This was recognised by the theoreticians, and it unfortunately appears to be the case that in the real world the discrepancy between what we observe and what linear theory would predict operates against us. We don't seem to be able to get greatly above a capture ratio of 1. We went to a lot of trouble in these experiments to keep the formation of eddies and vortices to a minimum so that is not the primary cause of the discrepancy; it is just the inherent non-linearity associated with large amplitudes of response.

Figure 7 shows the frequency response (efficiency against frequency), which is to be compared with the curves in Figure 4 for the two-dimensional model. Figure 7 gives results with plate and without plate; the plate helps a little, but not enough to get the bandwidths sufficiently broad to be of practical interest. The bandwidth of even the best curve is very much narrower than the crudest symmetrical two-dimensional water column. So three-dimensional columns don't really look as if they are a practical proposition; we have concentrated most of our efforts on two-dimensional column arrangements.

When we start to think about the problem of real wavepower devices we should keep very much to the fore the fact that wave energy is associated with very large forces; an essential fundamental question, probably the most basic question that we can ask, is "how are we going to react these forces?" Figure 8 shows the three options that are open to us – each is practicable. The first one is probably restricted to shallow water applications. As most of the resource is in deep water it doesn't represent a total solution to the problem; we may be able to put some very effective devices on the good sites, but for the rest of the resource we need to look for something
HANDLING THE LARGE CYCLIC FORCES ON THE COLUMN

1. Transmit them to the sea-bed
2. Transmit them to adjacent waves
3. React them against local inertia forces

This cancellation of wave components explains how that plate has a very high added mass, but zero added damping. This combination, of course, is exactly what we are looking for, and gives a clue as to how we might be able to get a good wave energy device. In the case of a free-floating water column, the number of degrees of freedom is much greater and the problem involves more components, but the principle is the same. If we can get all the components generated on one side by the device's heave surge and pitch and the motions of the column to cancel, and all the radiated components on the other side to cancel, the net effect will be the total absorption of the incoming wave. The model in Figure 11 is able to achieve wave cancellation in that way to a very useful degree; showing that it can be done in practice, as well as in principle, with a device of reasonably modest proportions has perhaps
been the main thing that we have been able to contribute to the ideas of wave power. We found it very exciting at the time and regard it as something of a breakthrough. The dimensions are indeed really quite modest in relation to the geometry of the waves; the depth to the horizontal plate is about 1/10th of a wavelength, and the total dimension from front to back is about a quarter of a wavelength.

Figure 12 compares the efficiency that we measure for the model in Figure 11 and the fixed version which we saw earlier. Although we get a good peak efficiency because of wave cancellation, in this case we didn’t get complete cancellation, and that accounts for the gap between the curves. We don’t get such a broad bandwidth; that is part of the penalty we pay for this particular approach. By more work and more effort optimization might close the gap a little bit but a fairly compact floating device will never reach the performance of the fixed version. However, we still have a device with a useful efficiency curve and bandwidth, with which it is possible to extract over 50% of the energy from a typical location in the ocean during a year. However, it would probably be more economic to aim for a slightly lower figure than the maximum; somewhere in the region of 30 to 40% mean annual sea efficiency is practical with that arrangement.

Figure 13 shows a selection of some of the shapes we tried. The lowest three all exhibit the kind of performance we have been looking at, and are all broadly similar in shape. The first two radically different ones didn’t work at all well, with peak efficiencies well below 50% in the first case, and just below 50% in the second. The fourth shape is the model in which we first observed wave cancellation; it was very interesting to see it at the time, moving around but with a millpond behind it. It was an exciting time for us when we appreciated the significance of what we were seeing. The difference in performance between the fourth and fifth shapes is not sufficient to justify the extra bulk, so the fifth shape is preferred; filling in its diagonal is an optional extra - it improves the performance a bit, but we would decide whether or not to do it on structural and perhaps launching considerations. The third shape came along later in fact, and might be a more practical shape if made out of reinforced concrete.

In the narrow tank we also made some measurements of mooring force in regular waves of moderate steepness, with different amplitudes and frequencies. Figure 14 shows the correlation between the measured mean mooring force and the theoretical value derived from theory using the idea of radiation stress: the results seem to confirm the theory. Those forces are very much less than the large cyclic wave-by-wave forces that I referred to earlier, and in principle they are the only forces that are felt by the mooring. However, it would be a mistake to infer that the mooring problem is going to be trivial and easy to crack; I’ll be saying more about the mooring later.

Now I turn to the question of how we are to extract the energy from the column. The most obvious thing to do is to replace the orifice we used in our experimental models with an air turbine. In this case the most obvious approach is the best approach, because the diameter of a turbine to match the head and flow made available by the column is very much smaller than the column itself (see Figure 15). Those who are used to the different characteristics of positive displacement and rotor dynamic machines won’t be surprised by this. The combination of column and turbine can be regarded as a pneumatic gear; the significance of this lies again in the problem of wave force. Wave energy is inherently associated with high forces moving at low velocities. In this arrangement,
by the time we get to the first piece of machinery, we have transformed it to high velocity and low force, and that gives us a head start.

But is an air turbine able to satisfy all the requirements of the wave energy device? Figure 16 lists what I think are the dominant ones. First of all we need to rectify at some point in the system, if the generator (and we have generally been thinking about electrical generation) can rotate in one direction only. Alternating generators are not really practical as the torques associated with the accelerations are excessive; somewhere along the line we must rectify. Self-rectifying turbines have been proposed, and they are possibilities, but at the moment we are thinking in terms of using a system of valves to rectify the flow before it gets to the turbine.

I mention that first because it’s relevant to what I think is perhaps the dominant design criterion in the secondary system; we will be hearing more about this from later speakers – we want the device to be efficient. Many people say that wavepower has to be cost-effective, that efficiency as such doesn’t matter because the waves are free. There’s a lot in that view, but in practice cost-effectiveness and efficiency go hand in hand; we put a very high store on trying to identify the most efficient system. That applies not only to the rectification but to the turbine itself, which has to be efficient over a very wide range of flow rates reflecting the random nature of the input from the wave. One can always get a wider range if one is prepared to use a variable geometry machine, so there we make a concession towards complexity; it makes for a longer development time, but a very much better final product. This particular arrangement we have in mind would have adjustable stator vanes; the concept here is new, varying the adjustment continually throughout the wave cycle to the instantaneous flowrate.

The need for a linear characteristic comes back to impedance matching and the relationship between the power take-off system and the column. We know that if the turbine has a linear head flow characteristic the column will continue to work well in all wave conditions, and a Francis turbine gives us a characteristic sufficiently close to that. The Francis turbine is also very efficient, and it is robust, which leads on to the next requirement of reliability. Reliability is also perhaps more associated with whether the equipment is accessible and replaceable at sea; the air turbine is relatively small, it is not in the water and in principle at least it can be got at for maintenance or replacement. Some degree of smoothing of the turbine’s power output before it gets to the generator is almost certainly desirable. We don’t quite know how much is necessary – the generator can certainly tolerate fluctuations and we are not talking about a machine which is connected synchronously to the grid. It looks as though a flywheel of reasonably modest proportions would be required; we are not talking about the massive flywheels needed for long-term storage.

The dissipation of excess power is also extremely important. You have seen on scatter diagrams just how much power there can be in the sea at certain times. The frequency response of the basic device will tend to shed some of the power in the longer waves, but there will be times when the column makes available to the turbine more power than it can economically be designed to handle. One of the beauties of the pneumatic system is the very easy way in which that power can be dissipated to some sort of throttle; it could even be the variable angle guide-frames I referred to earlier, and as it is open circuit there is no problem with heat build-up or heat exchanger requirement.

Water ingress is a disadvantage and potentially a problem with this sort of open circuit air system. By observing the devices in the wave tanks we are not unduly perturbed by it: we don’t think it is likely that large volumes of water will be thrust into the ducting and completely swamp the turbine, but some quantities of water will obviously get in. We think it will give sufficient protection to design into the duct water traps equipped with bilge pumps. The most likely source is for the water to come in from the outside rather than from the column itself. We are confident that it won’t come from the column if the damping is correctly maintained as the column behaves itself very nicely. Water from the outside provides a problem to which we can see fairly simple solutions.

Figure 17 is a schematic for those who perhaps couldn’t imagine what the valve system would be like. It will probably be self-evident that when the column is rising one pair of values is open and the air passes through the turbine from left to right; when the column is falling the air also passes through from left to right. The turbine still has to deal with a pulsating flow but not an oscillating flow. We envisage that in practice the valves would be hydraulically actuated louvre valves.
cross-sections much the same as the ones I have described. Figure 19 shows two sections joined together, and Figure 20 shows four. Figure 21 shows a comparison of the performance we measured with regular waves in the wide tank compared with the narrow tank, using the longest model with 10 sections. The efficiency is defined in relation to the length of the device, and is the mean efficiency for the 10 sections, adding all the chambers together. It is not surprising that the two curves agree quite well: we would expect two-dimensional approximation to be quite valid for a long device.

Figure 17

Figure 19

TURBINE EFFICIENCIES FOR STEADY FLOW AND NORMAL DISTRIBUTORS

Figure 18

Figure 20

Figure 21

I turn now to tank testing. In the last year we have been testing in the wide tank that Stephen Salter described this morning. We have made models in a number of sections with
The two are not identical however; Figure 22 shows results for the centre column, and for the end of the same 10-section model. The spikes on the curves are striking; the corresponding curves in a two-dimensional tank would in fact be quite smooth, but in three dimensions the situation is complicated by cross waves originating at the ends of the device. We can’t fully explain the spikes but we do believe that they are genuine, not just experimental error, and that’s why we have linked them together in that way. In general the middle columns do a bit better than in two dimensions, (probably all associated with the same cross wave phenomena), and the end ones do worse, in terms of peak and of bandwidth. Again that’s not surprising in view of what I was saying earlier about point absorbers; we are getting nearer to a point absorber at the end than at the middle.

Figure 22

Figure 23 shows some results measured in long-crested mixed-frequency or pseudo-random waves, with the device in its preferred configuration head-on to the waves. The solid curve shows the efficiencies predicted by applying the principle of linear superposition to the measurements in the narrow tank; there is generally good agreement. We have gone right round the edge of the Station India scatter diagram and the steeper waves tend to be appreciably less efficient than the shallower ones; this again confirms what we would have expected.

Figures 21 to 23 show the results of taking something conceived and developed in two dimensions and checking out that it does work in three dimensions as we would expect it to. We did look at one design parameter which is strictly a third dimensional one and that was how long we should make the device, how many sections it should have. In Figure 24 everything is normalized to the longest (10-section) model, with the waves at zero degrees. The curves show the effects of varying two parameters - device length and angle of orientation. Looking first at device length, it’s clear from the uppermost (0°) curve that the shorter models are not as good as the longer ones, as a larger proportion of sections are the less efficient end ones. There doesn’t seem to be much to be gained from making it longer than 10 sections, which would be 150 m long at full scale. A much longer model would have a large bending moment in the structure, and would need very specialised construction facilities; but the limiting criterion is that in a very long device the end columns would be forced down under the waves for long periods of time, and the turbine system would be flooded out.

The curves also show the effect of the angle of orientation. The efficiency drops off less rapidly than the cosine of the angle, which is very encouraging. This is just a test of an isolated model in a very wide tank, but it gives us a reasonable amount of confidence that the device would be able to extract about the same proportion of the energy actually incident upon it regardless of the direction. (I do not mean it will take the same total amount of energy regardless of the direction because the amount of energy incident on a long line of devices depends on the geometry of course.) We would need to do more elaborate experiments to confirm it, but that’s the assumption that we have made in estimating how well things would do at full scale. So the three-dimensional tank work has been largely an attempt to confirm what we had hoped and perhaps expected to be the case based on our two-dimensional work.

We have also looked at the rather different question of putting smaller devices in arrays. Figure 25 plots what has been defined as an interaction factor in studies by Ambli and Budal; the factor is the ratio of the amount of energy that would be
extracted by a point absorber in an array spaced at a variable distance compared with the amount it would extract by itself isolated in a wide sea. (The horizontal axis is the non-dimensional spacing; \( k \) is the wave number, so the axis measures \( 2\pi \) times the spacing divided by the wavelength.) We tested both point absorbers (our axisymmetric device shown in Figure 5) and our short two-section models; in tanks of different widths, formed by putting a moveable wall close to one end of Stephen Salter's tank. The results in Figure 25 are for the two-section model: they confirm the predicted trough where the interaction between devices is unfavourable, but in much the same way as with the point absorber, we were unable to get the peak. Linear theory doesn't apply when the amplitudes get big. Figure 26 summarises all these results, plotting the sea efficiency ratio against device spacing; the curve is pretty flat, and short devices remain inferior to longer ones.

Based on the data that we have acquired from these tank tests and the estimates we have made for the turbine, we have carried out a design study. We did this in collaboration with a local firm of consulting engineers, Roxburgh & Partners, and with Lithgows Ltd, the well-known shipbuilders on the lower Clyde. This was a fairly comprehensive study, but I will not go into it in great detail, because later on this afternoon there is a whole session devoted to the full-scale engineering of wave power devices; I will just summarize the main conclusions. Probably the most important finding was that devices of the type we have been modelling could be made and launched, using both reinforced concrete and steel. We are also confident that such devices could be operated and maintained out at sea and that they would survive. We can make these statements because of the fundamental characteristics of the device, the way it deals with the large cyclic wave forces. At no point in the system do these forces manifest themselves as point loads, or large bending moments; they appear just as pressures around the surface of the structure. So this presents a design problem not very much different from the hull of a ship; because the equipment is out of the water and accessible it is fair to say that it is a practicable proposition. We also believe that the device could be moored, but we must have much bigger reservations about how much rope is needed, and how long it would last. We are unsure about the dynamics of the moored system, and even more unsure about the cyclic life capabilities of the ropes. The kind of mooring we have in mind is based on nylon ropes, and the compliance is achieved through the strain energy capacity of the rope; this could be the cheapest method. Looking to the future, one might imagine that materials with better strain energy capacity and better cyclic lives than we have today could become available; many branches of technological progress are based on improved materials.

So we think we have come up with something that is practicable, which was what we set out to do. That is a significant step forward; but, as has been strongly emphasised, the concept so far is not going to be economic -
the sheer bulk of the structure, the magnitude of the mooring, and the low power rating combine to make the energy produced very expensive. We are now concentrating on looking at alternative configurations of the oscillating water column. We hope to find out more about these, and learn more about the problems we face, and so make more progress towards our ultimate goal.

DISCUSSION

P Bullman (Engineering Design Partnership)

When you have water columns arranged in an array of ten, have you considered bringing air flows together to a single turbine, which will perhaps not have the same problems of pulsing as when you have separate turbines in each column?

R Meir

We have certainly considered this. We didn't think that a fixed head could give the right matching for every wave in a random sea; something with a linear characteristic would be more efficient. The emphasis was on efficiency all the time as far as possible. That may not be the best solution because as you say it imposes a more strenuous duty on the turbine, which has to deal with larger pulsations. Possibly what one gains in sea extraction efficiency with the method we have used, one may lose in turbine conversion efficiency. I think it will be a fairly finely-balanced choice; both options are open and worthy of further investigation.

J Falnes (Technical University of Norway)

How many tonnes of concrete do you need in a full-scale converter, producing 1 megawatt on average, for instance?

R Meir

The reinforced concrete design is about 120 m long, displaces about 100 000 tonnes, contains about 50 000 tonnes of reinforced concrete, and has a rated output of 4 megawatts with an estimated load factor of 8%. This was just a preliminary design study, of course; no attempt was made at optimisation. It's quite clear that optimisation wouldn't change the conclusion that it's uneconomic -- we must look for changes that are more radical than merely optimising it; nevertheless it's worth mentioning that the design was not in any way optimised or perfectly matched. The steel design has a smaller displacement, 60 000 tonnes, and about 15 to 20% of that is structural steelwork. You also asked an earlier speaker about mooring forces. We estimate the mean drift force would be about 5 tonnes/m, allowing for wind, current, and wave drift, so the mooring force would be 600 tonnes. I am not too sure what the ratio between peak and mean mooring force would be; looking at those slow drift oscillations it is going to be quite large. Building in more compliance isn't in itself going to reduce this ratio, because you get a subharmonic oscillation, but there is a possibility for reducing it. One of the methods for dealing with unwanted vibrations is to build some damper into the system. The problem of course is to find a damper which is practical in this particular case. If one can be found, the ratio between peak and mean mooring force may not be so great. There is a challenge for the audience: if you can invent a compact and reliable piece of hardware to damp slow drift oscillations, you will be a very welcome visitor to the wave energy community.

J G Duggan (National Board for Science and Technology, Dublin)

This morning Dr Clarke gave us a load factor of around 20%; you there mentioned a figure of 8%. Getting down to that level it is very difficult to make anything economic in the area. Was there a particular reason why your load factor came as low as 8%?

R Meir

Yes: we haven't optimised the design -- that's really the reason. We just chose some reasonable numbers and worked them through and came up with the answer. Optimising the load factor on the basis of minimising the cost of the output is a much more difficult exercise, and at this stage it is not worth doing. Optimising it does not really change the overall conclusion. The design was over-rated at 4 megawatts; we could perhaps have rated it at 1.5 or 2 megawatts and not lowered the mean output very much. That gives a load factor of 15 to 20%; if you aim at a load factor higher than that, it starts to eat away at the mean output. There is a fundamental conflict here: we are talking about an insurance policy in national terms and we want to try and extract as much of the energy as we can -- it is not just a question of extracting it as cheaply as we can. Highly-rated devices are good on resource but not so good on economics; somewhere along the line one has to make the trade-off decision.

J M Dawson (Rendel Palmer & Tritton)

The rating figure quoted this morning was at the far end of the transmission line; could you make it clear whether that 8% was the same? It depends very much on which part of the power chain you are looking at; the closer you get to the waves, the lower the annual load factor becomes.

R Meir

Yes, this is obviously an important point. The figures I have been using were also quoted at the far end of the line.

J M Burnett (Merz & McLellan)

The advantage of ducting the air to a single turbine seems to me that it reduces the switching problem of getting the energy ashore.

R Meir

In principle that could be so, if you were able to duct a very large number of columns. With the concept I have been outlining, of a fairly compact more-or-less rigid floating monolith, there isn't much smoothing to be had anyway. The device is about a wavelength long, less than a crest-length; you would need to link the output from very many modules to get a significant benefit of the type you are describing. However, if it were a bottom-standing device in shallow water, this would start to look more attractive as a possibility. Where we do have good sites, we are coming round to the view that bottom-standing would be better than free-floating, and this is one of the reasons.

N S Miller (Glasgow University)

Have you examined the question of scale effect on your predictions? The type of device you have described is very similar to air-spring devices used for stabilisation, and we do know that there is a tremendous scale effect between a tank test and the full scale.

R Meir

Yes, that is a very valid point. We scaled according to the Froude number, of course. We have no evidence that Reynolds number is going to hazard or invalidate the scaling significantly, but Mach number will have some effect as you say -- the compression ratio is important. In the model scales the compression ratio is down at about 1.001:1 so we are talking about virtually incompressible; at full scale it's about 1.1:1; maybe 1.5:1 -- compressibility effects will be present. We haven't analysed this rigorously in a sense of building up an elaborate numerical model in a time domain, or even by carrying out experiments, but by calculating the value of an equivalent spring and comparing that with the buoyancy stiffness. We are just making some very simple (but very valid
and sufficiently informative) dynamic models – putting in this extra spring constant and seeing how it affects the device. It is not that significant. The extra spring constant raises the natural frequency of the column a bit, but that doesn’t necessarily mean that the device gets bigger. It also changes the optimum damping; but it does not invalidate the concept and at this stage it does not change the numbers to a significant extent. Of course, if we went to full scale and developed an actual device while forgetting about scale effects, we would be making a mistake.
The KaiMei project is the subject of an agreement made earlier this year between several countries of the International Energy Agency (IEA) to collaborate in the development of wave energy. The countries concerned, Canada, Japan, the USA, and the UK, agreed to collaborate in the development and testing of a full-scale device in the Sea of Japan based upon the oscillating water column of Yoshio Masuda.

The device is based on a ship-like buoy developed from model tests on a number of different configurations by the Japanese Marine Science and Technology Centre. Figure 1 shows the KaiMei at sea; it is 80 m long by 12 m in breadth and displaces some 500 tonnes.

The generating system depends upon 11 pairs of air chambers open to the sea at the bottom and closed by the
Figure 8

Deck at the top, except for a port above which is placed an air turbine driving a generator, and the associated rectifying valves. Figures 2 to 8 show various details of the device.

The KaiMei will be moored off Yura facing WNW since the maximum winds are predominantly from between W and NW. The fetch is open to the W for about 1000 km and to the NW for about 700 km, as shown in Figure 9. Wind speeds reach 50 knots or more during the winter and generate maximum wave heights of up to 12 m. Significant wave heights are more than 3 m for 30% of the time and more than 1 m for 70% of the time. Comparison shows the frequency of gales in the Sea of Japan to be 1/3rd that of the North Atlantic and North Pacific oceans. The main wave energy is concentrated in waves of 6 - 8 second period, or wavelength 60 - 100 m.

Although the KaiMei displaces only 500 tonnes, the water contained by the air chambers is estimated to weigh some 2,500 tonnes so that the virtual mass in surge motion will behave as some 5000 tonnes. These forces, together with the overall size of KaiMei, which is comparable with that of a normal 2000 tonne ship, demand very substantial mooring arrangements. These are shown in Figures 10 to 12.

The first tests at sea are being carried out during the present winter – from September 1978 to March 1979 – and the buoy is carrying three turbine-generator units of Japanese design, mounted respectively one near the bows, one near the stern, and one amidships. Each generator has a capacity of 125 kW, and the power from them is dissipated in a resistor bank.

The buoy will be brought back to harbour in spring 1979.
following which an additional seven or so generators, including one from the UK and one from the USA, will be added, giving the unit a total installed capacity of 1 to 2 MW. The second sea trial is timed to start in late summer 1979 and the buoy is planned to remain at sea throughout the winter.

The UK generator-turbine package is being constructed now. The design is shown schematically in Figure 13; the four valves rectify the air flow through the turbine. Figure 14 shows a more detailed pictorial arrangement. The main components of the UK contribution are:

- an air turbine
- an electrical generator
- a valve system for rectifying the oscillating air flow

The flow of air to the turbine is estimated to be 19 m³/sec at the design point and 32 m³/sec at maximum power giving estimated outputs of 110 kW and 300 kW respectively up to 200 volts. This power will also be dissipated in a resistor bank.

The valve system, for a wave period of 6-8 seconds, will need to change position every 3-4 seconds in about 0.5 second. As well as being mechanically reliable, the valves will have to ensure that less than 5% of the total turbine air flow leaks through them in the closed position.
The power-limiting valve is designed to avoid excessive power output from the generator in high seas. It is a relatively simple loaded plate designed to open at 0.117 kg/cm² and capable of passing up to 20 m³/sec of air, corresponding to the flowrate produced by a wave having a significant height of 8 m — that is, the kind of wave recorded once in four years.

The UK package is expected to be self-contained. The quantities to be measured will include at least the following:
- generator output — current and voltage
- pump room air pressure
- pressure head across turbine
- turbine and generator speed
- the signal from the wave-data buoy.

The results from the KaiMei project are expected to benefit the UK Wave Energy programme in various areas, both in the sense of being related to UK devices based on similar principles and to other devices working on different principles. The various areas of relevance are:
- the performance of an air turbine operating with an oscillating power input
- the behaviour of turbine/generator materials in a salty environment
- the behaviour of rectifier valves and the effects of their timing on the turbine-generator system
- the correlation of mooring forces with wave input
- the provision of basic data on wave energy capture width
- the provision of information on probable costs of larger-scale equipment.

We are now looking at very broad concepts here; the design philosophy which has been used in designing the UK package is basically one of reliability rather than efficiency being sought at this stage.

**DISCUSSION**

N A Gardiner (Railko Ltd)
Could you give some indication of the rotating speed of the turbines?

Dr J Butterworth
Of course it depends upon the air velocity, but it is around a maximum of 1200 revolutions per minute.

D Ross (Journalist)
The question is to both the last speakers. Isn’t it becoming rather evident that in Britain we are seeing the alternatives of efficiency and cost-effectiveness as the only realistic things and that in the end, possibly by the early decades of the next century, we shall have a very high percentage of zero while the Japanese are going ahead now and producing something which is being described as reliable rather than efficient, but is producing energy?

Dr J Butterworth
The design philosophy that I enunciated is for the UK package, so the UK package will be reliable. The efficiency of course is what we are hoping to measure. Whatever system we have, efficient, or inefficient, the criterion of cost-effectiveness must apply in the end, when the device is connected to a realistic power system. That time is quite a distance away yet and, as one speaker said this morning, there are many real problems to be faced before then.

Professor D T Swift-Hook (CEGB)
The suggestion that David Ross seems to have made is that there is a difference between efficiency and cost-effectiveness when your energy comes for free. I am afraid that just doesn’t hold water, if that’s the right phrase in this context. The point is that your total absolute cost is normally broadly proportional to the total amount of energy that you are capturing or handling. The price that you expect to pay is going to be proportional to your useful power output, not your power input. The ratio between power output and input is commonly called efficiency and so the price per kilowatt out is exactly inversely proportional to efficiency; going for high efficiency is the same thing as going for low capital cost, for a given size of device. I really don’t see the difference in philosophy. Of course if you don’t also have a high reliability coupled with your high efficiency you lose all your cost benefits, but that’s a different question. High efficiency is essential for good cost benefits even when your energy comes for free.

Dr J Butterworth
I would not wish to dissent from a word of what Dr Swift-Hook has said.
In tracing the development of the HRS rectifier one has to go back some 20 years or so. At that time HRS were invited to investigate the possibility of harnessing the steady swell breaking on the coral reefs offshore from Mauritius. The proposal was to cap the coral reef with a sloping sea wall so that the waves would run up the ramp and raise the water level in the lagoon behind the reef. This was a reasonable proposition because the tidal range was insignificant. The impounded water was to have been passed through low head turbines and back into the sea. Unfortunately this half-wave rectification system was very inefficient and uneconomic.

In passing it is interesting to note that a peristaltic device was devised at this time. It consisted of a flexible pipe containing non-return flap valves spaced along its length. The pipe was laid on the bed, normal to the wave crests, and as each wave passed over its length a plug of water was squeezed along the pipe ahead of the wave. It worked; small quantities of water were raised to modest heads. Some of the devices being considered now are reminiscent of this early device.

Over the intervening years the subject of wave power was raised from time to time but only examined cursorily until late 1975 when the subject began to arouse general interest elsewhere. It was appreciated that the Mauritian scheme had a low efficiency for many reasons, but principally because it was a half-wave rectification system, making use of the wave crests only. If only one could make use of the troughs as well. This line of thought led Mr Russell to the concept of a series of compartments side by side as in Figure 1: alternate compartments were fitted with non-return flap valves, allowing water to enter, and the intervening compartments fitted with reverse sense flap valves allowing water to flow out. The inlet compartments would acquire water as the crests of waves moved on to the face of the structure thus raising the water level. The outlet compartments would lose water as the waves receded lowering their water level. Interconnection of alternate compartments would form high and low level reservoirs. Water flowing from the high to the low level reservoir could pass through a turbine and hence generate electricity.

In January 1976 a crude demonstration model (seen in Figure 2) was built to provide proof of concept – in the accepted parlance. At that time the device was thought of in terms of a floating structure with a cross-section something like that of a supertanker. There were six compartments, three inlet, three outlet, fitted with a series of narrow flap gates made from beryllium copper strip with rubber hinges. The outermost compartment that you can see is a low level compartment and top right is the end of the channel connecting the high level compartments. The low level compartments are connected immediately beneath this channel. Mounted at the back of the upper channel is a long paddle wheel which is driven by water passing from the upper reservoir to the lower reservoir. In turn this drives a hub dynamo – bought from a local cycle shop – which lights a tiny bulb. Having demonstrated the principle to be sound HRS received a contract from the Department of Energy in November 1976 to study the feasibility of the rectifier in greater detail.

Although the concept had developed along the lines of a floating structure, so that it could be moored out of sight of land, it was also recognised that the device could be placed on the sea-bed closer inshore. The first decision to be made was therefore which line of development should be followed – floating structure, bottom-standing structure or both. The main disadvantages of a floating ship-like structure were thought to be firstly the difficulty in providing sufficient torsional strength when one complete side would be permeable. Secondly there would be a need for buoyancy or trimming tanks. Although these might be the source of torsional strength they would add significantly to the structural cost. The third and by no means least disadvantage was the mooring problem. Close association with mooring problems over the years led us to believe that to provide a mooring system with an adequately low probability of failure would be very expensive if not uneconomic, 100% certainty of security being out of the question. Additionally a mooring system could add significantly to the maintenance costs.

For these reasons the first development was made to move the rectifier closer inshore and place it on the sea-bed avoiding the mooring problem and gaining structural support from the sea-bed. Having decided on a bottom-standing device the line of attack followed was the determination of the effect of the various parameters such as rectifier width,
compartment spacing, so that at the end of the day the optimum structure could be put together.

Before experiments could begin a crude analysis of the various factors had to be made in order that an adequate model could be constructed. Firstly consideration of the gates. It will be readily appreciated that if the horizontal excursion of the water beneath the wave is small compared with a gate width, the gate will barely open. The gate width to wave-height ratio had therefore to be small so that the excursion length would be many times the gate width. It was felt that a full size gate about half a metre wide would be about right.

There was another aspect of gate behaviour which had to be considered. Because the dynamic pressure of the waves decreased with depth and is opposed by a uniform net hydrostatic pressure due to level differences across the face of the rectifier the gates would want to open differentially in depth. This imposed the requirement for torsional flexibility in the vertically hinged gate system: horizontally hinged flaps would pose operational difficulties. These considerations led to the conclusion that a number of long narrow and torsionally flexible gates were required for each compartment.

The spacing of the compartment walls was arrived at by drawing an analogy with the classic case of diffraction of waves by a grating. Assuming the inlet and outlet compartment spacing to be equal, at an instant when one set of gates is open, the gates of alternate compartments will be closed. The front face of the rectifier would therefore present the appearance of a grating with equal widths to slots and spacings. The transmission of a wave through such a grating shows only a 2% loss of energy when the slot width is 1/10th of a wavelength and still only 7% at 1/5th of a wavelength. It was decided therefore that the compartments should not be more than 10 m wide.

The width of the rectifier, the back-to-front dimension, was also considered in relation to a wavelength. Ideally, a wave on entering the rectifier should have a sufficient distance to travel before on reflection from the back it returns to the gates and closes them prematurely. This criterion suggests that the rectifier should not be less than a quarter of a wavelength wide. Frrom these basic considerations the first model (Figure 3) was designed to a nominal scale of 1/30th.

I shall speak in terms of full-scale dimensions. The model was built to have two full section inlet compartments and one full section and two half section outlet compartments. Symmetry was necessary to avoid transverse resonances in the flume. The model occupied the full width of the flume resulting in a full section compartment width of 5.6 m. It was made so the back-to-front dimension could be varied from 25 m to 37.5 m and 50 m; at this time the depth of water being considered was 30 m.

The gates presented quite a problem. The small scale of the model called for fine tolerances. The solution was found in moulding, in rubber, a pair of thick gates joined by a thin sheet as an integral unit. These gates were mounted on cast-iron gate frames, each frame approximately 5 m high. This is perhaps the second development. Instead of gates running from top to bottom of the full scale device they would be constructed in banks and the banks mounted one upon the other (Figure 4).

In order to eliminate additional variables from the experiments which would have confused subsequent data analysis it was arranged to pump and meter the discharge from the high level to the low level reservoir. The simulation of power take-off would come at a later date. The experiments were run at various waveheights in the range 0.6 m to 5.5 m, at wave periods of 8, 10, 12 and 14 seconds. At each wave condition various reservoir discharges were imposed and the resulting level difference between upper and lower reservoirs measured.

Before showing you some of the results I think it might help your appreciation of what makes the rectifier 'tick' if I introduce you to a bowdlerised edition of the theoretical analysis that was carried out in parallel with the experimental work. First of all, how does the rectifier respond to varying the head difference between the reservoirs?

In Figure 5, when the levels in the reservoirs are at MWL — zero head difference — the flow into the inlet chambers and the flow out of the outlet chambers is a maximum. This is of
course for a completely free flow from upper to lower reservoir. As the flow between the reservoirs is reduced the level in the inlet chambers goes up and the level in the outlet chambers down reducing the flow to and from the rectifier to match the internal exchange flow. In the limit the head difference reaches a maximum and there is zero flow. In this condition the front face of the rectifier acts as a perfect reflector giving rise to a standing wave pattern with an amplitude twice that of the incident wave. The head difference between the reservoirs should therefore achieve a maximum value equal to twice the incident waveheight. Since the power available is related to the product of discharge and head, in the two extremes at maximum-head-zero-discharge and maximum-discharge-zero-head the power output must be zero. Somewhere in between these two extremes the power output must reach a maximum, but where and how much?

Figure 6 shows a plan view of the rectifier and a section, \( f(t) \) is the incident wave, \( g(t) \) the reflected wave and \( m(t) \) the wave entering the inlet compartment. Two conditions have to be satisfied. There must be continuity of the water surface at the face of the gates during the period they are open and there must be continuity of flow. These conditions give rise to two equations shown in Figure 6, which lead to an expression for power output: \( a \) is the amplitude of the incident wave and \( c \) its celerity; \( -\theta_0 \) is the phase angle at which the gates open and \( +\theta_0 \) the phase angle at which they close; \( \theta_0 \) as one might expect is related to the head difference \( h \) and the waveheight \( H \):

\[
\theta_0 = \cos^{-1} \left( \frac{h}{2H} \right)
\]

Dividing the power output by the incident wavepower gives the efficiency.

What does this result mean? In Figure 7 the efficiency reaches a not very impressive maximum of 31% at a head difference of about 0.8 of the waveheight. What happens to the rest of the energy? When the gates open the mean level in the upper reservoir rises until the gates close again. The mean level then falls steadily to the end of the cycle. The reverse happens in the low level reservoirs. Thus over a cycle the temporal mean head difference between the reservoirs is greater than the normal head difference. Taking this into account the expression for power becomes:

\[
\text{Power output} = \frac{8pga^2c}{3\pi} \left( \sin \theta_0 \cos \theta_0 - \sin \theta_0 \cos \theta_0 \right) \left( \cos \theta_0 + \gamma \left( 1 - \frac{\theta_0}{\pi} \right) \left( \sin \theta_0 - \theta_0 \cos \theta_0 \right) \right)
\]

where \( \gamma = \frac{1}{3} \left( \frac{W}{\lambda} \right) \) (\( \lambda = \) wavelength), and the efficiency is given by:

\[
\epsilon = \frac{16}{3\pi} \left( \sin \theta_0 - \theta_0 \cos \theta_0 \right) \left( \cos \theta_0 + \gamma \left( 1 - \frac{\theta_0}{\pi} \right) \left( \sin \theta_0 - \theta_0 \cos \theta_0 \right) \right)
\]

The maximum efficiency still occurs at a head difference of 0.8 of a waveheight but its value now depends upon the width of the rectifier (W).

Figure 8 plots the maximum efficiency for \( h/H \) equal to 0.8, as a function of the rectifier width multiplied by the wave number \( K \) that is to say by \( 2\pi/\lambda \). The maximum efficiency has now risen to 50% and this occurs when the rectifier width is

![Figure 6](image-url)

![Figure 7](image-url)
than those higher up. In shallower water the difference in orbital motion decreases with depth so that the gates lower down function less efficiently. This plot gives another interesting piece of information. The maximum efficiency measured was 69%. The analysis can be extended further to take internal resonances into account. In Figure 9 an additional wave \( \eta(t) \) is introduced and a third equation is obtained from balancing the flows due to the wave \( m(t+\phi) \cdot \eta(t+\phi) \) and the discharge \( Q, \phi \) being the phase shift between the front and the back of the rectifier. Unfortunately there is no formal solution and one has to obtain answers via an iterative process. Furthermore it does not lend itself to modification to take account of things like gate action.

\[ \eta(t+\phi) = \frac{m(t+\phi)}{Q}. \]

How do the results obtained from the model compare with analysis? By selecting the efficiencies at \( h/3H \) equal to 0.8 from each experimental run and plotting against the width-to-wavelength ratio we have the picture given in Figure 10. The effect of internal resonance is clear. Around the quarter wavelength mode the efficiencies are enhanced and at the half wavelength mode they are depressed. I should point out that although analysis suggests that the maximum efficiency should occur at \( h/3H \) equal to 0.8 the results only showed tendencies this way. These points are therefore not maximum efficiencies. The maximum efficiency measured was 69%. This plot gives another interesting piece of information. The figures in brackets refer to the depth-to-wavelength ratio for each run. Although these tests were carried out at constant depth and various wavelengths they may be interpreted in terms of depth variation, (shallow water small number, deeper water larger number). You can see that there is a distinct effect on the efficiency in deeper water to be lower. This is not due to the effect of depth on wavelength, because this is accounted for in the \( W/A \) parameter. It is principally due to the gate action. In deeper water the orbital motion decreases with depth so that the gates lower down function less efficiently than those higher up. In shallower water the difference in orbital motion from bed to surface is less – and also the horizontal orbits are increased for a given waveheight. Therefore in shallower water the gates function more efficiently.

Depth therefore appears to be an important variable in the optimisation of the rectifier. Obviously its height is reduced by moving into shallower water. In shallower water the wavelength is reduced, therefore for maximum efficiency it can be made narrower. The third effect is on the gate performance and finally there is a decrease in frequency dependence in shallow water. In deep water the wavelength is proportional to the wave period squared but in shallow water it varies linearly with period. For an optimum width of rectifier in deep water the performance range for waves between 8 seconds and 14 seconds would lie between \( W/A = 0.3 \) and \( W/A = 0.1 \). In 15 m of water this range is reduced to 0.27 and 0.14. Perhaps a point should be made here. Although at first sight the rectifier appears to be considerably frequency-dependent I think you will agree that over the working range it is not so significant.

Understandably the next development of the rectifier was to move it from 30 m of water to a depth of 15 m. It was thought that even at this depth there would be no significant loss of energy due to waves breaking. Unfortunately the construction of next model was started, in order to get experimental continuity, before the previous experiments were complete and hence before the influence of the main variables had been assessed. The main purpose of the next model (shown in Figure 11) was to introduce what was considered to be a desirable structural feature. By introducing a 1 in 3 ramp leading into the inlet chambers the intrusion of sediment would be inhibited, and the distribution of flow to the outlet chambers improved. Another modification was to the gates: there was no point in having outlet gates above MWL and so above this level all the gates were inlet and the low level chambers were roofed over and vented. The width is now 40 m and the water depth 23 m.

This model introduced two new variables, the slope itself and the crest level of the slope which was 2.6 m below MWL. When waves run up a gentle slope the wavelength gradually shortens but when the slope is steep and short compared with a wavelength the waves are reflected. In effect the ramps within the inlet compartments made the rectifier behave as if it was narrower than its full width. This point is illustrated by the results plotted in Figure 12. Maximum efficiency now appears at \( W/A = 0.3 \). However the crest level has a pronounced effect upon this behaviour. Tests carried out varying the crest level suggest that with a crest level set at 5 m below MWL the performance would approach that of the earlier model.

So far nothing has been said about the turbines. At the outset it was thought that the heads would be too low and the quantities of water too vast for conventional machines so that...
the paddle wheel would have to be reinvented in the form of a paddle drum with all that 20th century technology could bring to bear. However the National Engineering Laboratory who were given the job of sorting this problem out for us considered every conceivable device and came back with the answer that, although at the bottom end of the range, a Kaplan turbine would do the job. A possible alternative would be a bulb turbine. When the rectifier was standing in 30 m of water and was wider it could conveniently contain a Kaplan turbine and its draft tube. Now that it stands in 15 m of water the rectifier is much smaller and the turbine would have to be housed in a rearward extension to the caisson. Also the reduced depth makes it barely possible to include an adequate draft tube. Thoughts must now turn toward the bulb turbine but the ultimate choice is bound up intimately with structural considerations. The hydraulic investigations have defined the target area fairly closely for the optimisation of the structure from the design and construction point of view. It is from this direction that the next major development will come. That is not to say that there is no more hydraulic work to be done. The work in hand at the moment is to measure the extreme values of the forces and pressures on a model, built to the optimum dimensions, in random waves and at the same time monitor its performance. Following this three-dimensional tests are projected.

DISCUSSION

J Berry (Bertlin & Partners)
I think you have got something which is eminently practicable from the civil engineering point of view in that it looks perfectly conventional. I don't see any technology problems at least with the civil engineering. However from our own experience we know that there are quite often problems with debris tending to jam the gates. For example, on a current job where we have rubber meeting faces, there has been damage due to debris; of course when you go along and look at it, it never happens while you are actually there but I think this is a real danger. Obviously one way is to put a grizzly or screens in front, but the trouble is that you will lose some power. Has this potential problem with the gates been looked at any further?

P J Rance
Normally one is considering the drift due to waves and the drift due to winds in an uninterrupted situation but if you have the same drifts coming up against a barrier, then something has to give. As far as the wave-induced and wind-induced drifts are concerned the rectifier appears as a reflector and the tendency is for a circulation pattern to form in front so that debris tends to stand off in a trashline. We did in fact look at this in the model; if you drop matchsticks in front of the model they do drift offshore to form a trashline. That is not to say that there is no problem: there will be a slight problem, but it will not be carried across in large quantities. I don't think one need bother too much about the gates themselves getting damaged: we envisage that the prototype gates will be reinforced, in thick rubber waisting down to a thin rubber hinge with the reinforcing going down to the neutral axis and out again. It has been suggested that we might get clogged up with seaweed, but I think that the amount that would diffuse across the trashline would be relatively small and not present too much of a problem. We would screen at the intake to the turbine rather than along the face of the rectifier, perhaps with a moving band screen and onto a conveyor belt and away.

W Haley (Lawrence Allison)
This device appears to be very similar to a tidal barrier scheme with the dimensions of the structure and type of turbines very similar to a hydroplant. Would you consider any collaboration with tidal barrier groups?

P J Rance
We are also, as a research station, concerned with tidal power, and we do recognize the similarity. The main problem at the moment is one of structural innovation to get the costs down; we are now on the point of linking up with a firm who we hope will hold our hands in this direction – in fact they would take the lead and we would become hydraulic advisers to them.

D MacGregor (Biarritz, France)
Have you made any calculations of the relationship between the installed costs and the power available?

P J Rance
Quite early on we did a form of optimisation. It was based on a wave-by-wave accounting system, ascribing a Rayleigh distribution to each box in the scatter diagram; this was necessary because we considered limiting the height of the structure for economic reasons (so that extreme waves would sail over the top) and one can really only tackle this on a wave-by-wave basis. That optimisation was merely an academic exercise. Until we have the civil engineering input into the investigation I think the answer must be no, we haven't done any optimisation in that direction.
The Vickers wave energy device is being developed by the Design & Projects Division who are the major contractors of the Vickers Engineering Group. In this Division we are continually looking at new outlets for our engineering abilities. Our wave energy device was evolved from consideration of ways in which the hostile air/water interface, mooring problems, and the need for complex mechanisms could be avoided. We felt that wave energy conversion needed a fundamentally new approach. The principle used was that of an oscillating water column activated by the change in head of the wave passing over it. If the column length is made so that the natural frequency of the water column is equal to the natural frequency of the waves then the water column will resonate with a resultant amplification of wave height. This amplification implies that the column is capturing energy from a wider area and is therefore a more effective wave energy converter. The principle is, of course, that of a mass-spring damper system (see Figure 1).

![Figure 1](image1.png)

With a single inverted U-tube the two oscillating columns interfere with each other, as is shown in Figure 2. There is also the problem that the relative motion of the two columns is affected by changes in the wave frequency. A single column is a more satisfactory device and by having an enclosed air volume the column can be submerged. The pressure of the air volume is adjusted to give the correct column length. The alternative single column solutions are shown in Figure 3. Our intention was to make the device more compact and the solution shown in the centre gave minimum duct losses but a downward-facing inlet. It was clear, both from our own work and from theory presented by Professor Sir James Lighthill, that an upward-facing inlet gave improved performance. The wave power decreases exponentially with depth and for a given device height an upward facing inlet can be placed nearer the surface than a downward facing inlet and therefore seize more of the wave power. It is essential to the operation of the device that it does not move horizontally as this could affect the wave frequency relative to the device. The upward-facing duct also enables the device to be piled to the sea bed. With this method the structure can be designed to withstand the side loads imposed on the device and we therefore settled on the configuration shown on the right of Figure 3.

![Figure 3](image3.png)

Our favourite method of flow rectification is to let part of the oscillating column overtop into a reservoir at the top of each stroke (see Figure 4). Initially the extra water collects in the reservoir, pressurizing the air volume above its static pressure, that is atmosphere plus depth of interface. A controlled flow is then allowed through a low-head turbine. This system has been investigated, in parallel with our own work, by Professor Sir James Lighthill at Cambridge and Dr Graeme Knott of Sussex University, both of whom have given us encouraging results. The graph in Figure 5 was prepared by Dr Knott. The vertical axis is the power ratio, that is the theoretical ratio of the actual power to the optimum linear power at resonant frequency; the horizontal axis is the frequency ratio, the ratio

![Figure 2](image2.png)

![Figure 4](image4.png)
of the frequency to the resonant frequency. It can be seen that, at frequencies below resonance, our over-topping device generally has a higher theoretical power extraction rate than an equivalent linear device.

We started our experimental programme in a wave tank using various plain perspex tubes; we then added a collecting tray and investigated over-topping with the simple model shown in Figure 6. The outlet of this model was then enclosed and connected to a large air volume as in Figure 7. At such small scale, approximately 1/100th, scaling the air volume presents a problem because the facilities are not available in this country to work at 1/100th scale atmosphere. We overcame this problem by connecting our submerged models to a large air volume outside the actual wave tank. Figure 8 demonstrates the minimum duct loss configuration, but the arrangement caused far too much blockage in the existing small wave tank at Lancaster University which we were using. The plenum chamber, as you can see, effectively destroyed the waves before the device saw them. When the current model with an upward-facing inlet, shown in Figure 9, was installed the situation was very much improved. The base of the model is connected to the external air volume already mentioned as necessary due to scale effects. At full
scale this will not be required, and the equivalent inlet depth to our experimental test depth would be 8 m. At the resonant frequency of 0.9 Hz there is vigorous over-topping and 93% of the available power in the wave is absorbed in the model.

On the graph in Figure 10 you can see we have obtained over 0.4 W at resonance with a 2.5 cm amplitude wave and optimal over-topping height. A simpler and more realistic approach is to use a fixed over-topping height, and the graph also shows results for a 15 mm height; although the maximum power is reduced, the bandwidth is improved.

In a few weeks' time we are hoping to use Prof French's new tank at Lancaster University where we will be able to investigate the effects of inlet depth on the model which we are unable to do in the smaller tank. We expect the experimental work on this improved facility to continue to be encouraging and it is our intention to move to pilot scale with parallel theoretical studies of the full-scale device. We are well aware of the problems that have to be solved before the device can become a full-scale reality as is depicted in the artist's impression in Figure 11. However, if it is valid to scale up these experimental results by a factor of 100 to represent full-scale operation, this would give a hydraulic power of over 4 MW at resonance for a 2.5 m amplitude wave over a wavelength of 120 m.

We see areas for improving the device's performance and cost-effectiveness – particularly with regard to the volume of air containment and increasing the hydraulic head of the device. With any wave power device there are new frontiers to be crossed in almost every area, whether these are of a technical, constructional or operational nature. We believe that the concept I have outlined minimizes the scale of the problems facing us. We at Vickers look forward to bringing our own device to a viable reality, and perhaps to giving support to other parts of the wave power programme.

**DISCUSSION**

**J M P Soper (Sea Energy Associates Ltd)**

Could I ask Mr Chester-Browne what hydraulic heads he is thinking about at the moment for his device? He mentioned that he was looking to improve these: what is he considering at the moment and what does he hope that he might be able to improve the head to?

**C V Chester-Browne**

We are achieving the equivalent at the moment of 1½ m. It's difficult to give any realistic figure for our hopes at the moment because it depends on whether some of the ideas which we are working on bear fruit; we haven't yet got them to the experimental stage, but we would hope to improve on that figure very considerably.
THE FLEXIBLE BAG WAVE POWER DEVICE
Prof M J French (University of Lancaster)

Design Philosophy
If wave power is to be used then converter costs must be kept as low as possible. Low costs can be achieved by:
- high energy transfer rates per unit area of collector working surface (say, 1 kW/m²)
- high ratios of collector working surface area to device volume (say, 0.2 m⁻¹)
- inherently cheap construction.

The first can be achieved by resonant devices in monochromatic seas or by low mass-coupling and suitable loading in real seas (quasi-resonance). These considerations led to the choice of a flexible bag as the working surface, and to the orientation of that surface in the plane of the wave motion. A further important advantage of this arrangement is a high order of sea-kindliness. From this initial decision on the nature and orientation of the working surface the rest of the design follows naturally, with only one or two branch points.

The principal functions of a WEC are those of:
- a collector surface
- a force-balancing system
- a power transmission and conversion system.

The alternatives for force-balancing are firstly, sheer inertia, secondly, a wave-spanning structure, in which working forces react against one another, and thirdly, a rigid fixing to the seabed. The second seemed likely to be cheapest. For power transmission, low-pressure air in a closed circuit seemed intrinsically most promising and also the natural choice for a flexible membrane scheme.

Description of the Device
The device (Figure 1) consists of a long beam lying head to sea and kept afloat by flexible air bags attached along its top. These bags (Figure 2) communicate via non-return valves with two longitudinal air ducts formed in the beam: as a wave crest rises round a bag, the air is squeezed out of it into the 'high-pressure' duct; as the water level falls again, the bag fills again from the 'low-pressure' duct. Thus each bag works more or less independently as a simple bellows, pumping air from 'low' to 'high' pressure: the terms 'high' and 'low' are relative, the difference being a head of water equal to about half the prevailing wave height. The air-circuit is completed via two single-stage air turbines (on the same shaft) through which air returns from the 'high' to the 'low' pressure side. It is sometimes useful to think of the bags as collapsing in a crest, and so reducing its height, and expanding in a trough, which thus tends to be filled in.

The bags
The bags are formed in two ranges, each about 80 m long, with a continuous outer cover divided into about 10 separate bags by transverse membranes or septa. Preliminary tests have been made on suitable reinforced rubber materials which can easily meet the high strength requirements and are relatively cheap (ie in pounds per kilowatt). Manufacture does not appear to present serious difficulties. Nevertheless, questions of bag design and durability constitute the most critical area of uncertainty with this device, and may possibly make it impractical.

Operation
It is proposed that the devices should be operated in rows facing the prevailing wave direction. The need to swing clear means that spacing must be wider than might otherwise be desirable, but it is felt this arrangement will reduce mooring problems and hence costs. Although the general effect of the long ducts is to smooth the airflow to the turbines, there will be considerable pulsations in the duct pressures due to the irregular number of crests and troughs opposite the bags at any instant, and also the large fluctuations in wave height. It is proposed to adjust the nozzle blades of the turbines continuously to extract the maximum power, closing them more for high waves, and opening them more for low ones, with very little reaction in the former case and about 50% in the

The beam
The beam, or hull, is of prestressed concrete and of simple construction. It approximates to a box beam, the 'box' being divided into four to provide the two air ducts and two sets of water-ballast tanks. Present designs are about 190 m long, although there are indications now that a shorter device would be more economical.
and blowing of ballast by stored compressed air, all initiated by an automatic damage-control system. However, we have yet to provide firm performance results and, above all, we need to know if bag-life will be adequate.

Notes

1. **Bag form.** The walls of the bags sustain travelling waves, the midship peaks of which are opposite the crests of the sea, the outboard peaks being opposite the troughs. The form of their motion is much smoother than the trapezoidal shape which might be expected because of the interactions between one bag and the next. The variation of cross-sectional area is thus roughly sinusoidal.

2. **Characteristics.** Ideally, the bags should pump the same volume of air per wave, only the pressure varying with wave-height, so that power output might be expected to vary as height times frequency. In practice, the variation with period is small, with an apparent maximum around 9.5 s full scale. The variation with height is seen in Figure 3. These results are based on tests in which pitching is suppressed, however, and the full picture will not emerge until testing with an automatic system has been done. Our expectation is that performance will then improve. Also, at the small scale of 1/40th at which we currently test, it is impractical for us to make low-loss valves and crude flaps are used, although tests on valves only at 1/14 scale lead us to believe the losses can be made very small.

Reference


**DISCUSSION**

Dr G Owen (Heriot-Watt University)

Prof French mentioned that a single point mooring could be used to ensure that his WEC lined up with the wave direction. Has he considered the effect of low frequency drift oscillations that are typical of single point mooring systems? In that connection could he say something about the efficiency of the device as a function of the directionality of the waves? And could he say something about the capture width of his device?

Prof M J French

I think the case may be more favourable than that of a ship. In the very limited experiments we have done, the device has both ridden free without oscillations and shown long-period divergences. In the latter case the device was not functioning properly, which I suspect may affect its oscillatory behaviour. We don’t think the efficiency falls off with directionality very fast, but we are worried about the effect on the bag of running at a wide angle to the sea. The capture width is very variable of course because the bigger the waves get the narrower the capture width is. You can work this out from the power figures; I remember that at a typical design point it is about 120 m.
Brief details are given in this paper of some of the main features of the Queen's University wave energy device. First of all I would like to acknowledge the support of the Wolfson Foundation, which in the early days of this project provided us with funds. More recently funds have become available from the SRC and from the Department of Energy, and these are gratefully acknowledged. The initial exploratory work at Queen's University was carried out in the Electrical Engineering Department by Mr Alan Hidden, and I am glad to say that he is here today. It was largely due to his infectious enthusiasm for wave energy that in 1975 work began in the Civil Engineering Department under the direction of Prof Wells.

Figure 1 shows a number of different configurations that were initially considered; eventually we decided on an isolated hydro-pneumatic buoy system. The essential features of the system are shown in Figure 2. It consists of a pressure chamber which has a buoyancy compartment around the skirt; the pressure chamber is rigidly connected to a ballast chamber underneath (in this case a toroidal section) which is filled with water so that it resists vertical heave motion and so reduces the forces that have to be taken by the moorings. The power take-off utilizes the Wells turbine (which I shall be discussing in more detail later), directly coupled to a generator.

It would be useful to point out some of the features of this device which make it different from the other devices that have been considered here today. As it is essentially a point absorbing device, it can accept energy from any direction. The contained mass of water has the essential feature that it prevents vertical heave motion at the wavelengths which you would want to derive energy from, but when storm waves come on the scene it allows the device to ride them out. We have found from some of our tests that by incorporating flexible moorings we get a higher energy output, so in fact these are highly desirable. The fact that the system is a point absorber lends itself to a modular system of construction with corresponding cost savings. The final feature which is of great importance is the fact that the device incorporates a self-rectifying turbine with no need for flap valves.

As a series of waves pass the device an out-of-phase movement of the water surface inside the pressure chamber is induced. This change in inside water level relative to the buoy has the same effect as a piston in a cylinder such that air is expelled and sucked back in through the neck of the device. It is this cyclic air flow which activates the turbine.

A number of laboratory tests have been carried out; in the series shown in Figure 3 we were investigating the influence of different ballast systems on the performance of the device. We assessed 0.6 m and 0.44 m diameter spherical ballast chambers, a simple flat plate device and a toroidal system.
The conclusions from the hydrodynamic tests are that, although the efficiency might be slightly lower than for some of the other devices, the overall simplicity should compensate for this; the capture width, we feel, is somewhat greater than the buoy diameter even though the results are still only at 100% at the optimum condition. We feel that there is energy being absorbed around the side of the buoy as well as in front. The performance is essentially that of an oscillating water column system; we know this is the case from tests in which we have fixed the top canopy and determined the power extracted; we have found that when we allow heave motion to take place we get improved performance, so heave motion does in fact enhance the normal water column resonant condition.

The Wells turbine has been mentioned by other speakers today, and it is appropriate to illustrate how it works. In essence it is a symmetrical aerofoil section; when air flows in a vertical downward direction as shown in Figure 6 it will produce forward thrust. This forward thrust is produced equally well when the axial flow is in the opposite direction. So without any need for flap valves we have a system which is self-rectifying. Another advantage of the system is that it has a high rotational speed, which means that it can be coupled to readily available standard generators. The geometry of the cross-section is very simple, which would mean relatively low-cost construction. Thus overall the power take-off system is relatively straightforward. Figure 7 shows a possible three-stage turbine which could be incorporated in a full-scale device. Analytical studies carried out by the CEGB Marchwood Laboratories have indicated that a turbine of this type would have an efficiency at its optimum condition of the order of 80 to 85%.
some indication that there may well have been some power being extracted but we have no means of ensuring that this was the case.

Even so, I would confirm that these tests were extremely useful as real engineering problems had to be overcome. For example, we had to lift the buoy into position by means of helicopter. We found that for a buoy of this particular size glass-fibre reinforced plastic was ideal; this form of construction seems to have very good capabilities for energy absorption, and it is interesting to note that it was not the glass-fibre part of the construction that failed. During installation of the turbine generator (in this case a 45 kW alternator of the type normally used in aircraft) and all the electronics for monitoring, we found that these could easily be installed on site as a modular unit. Even though the device had a relatively large sphere at the bottom and looks highly unstable, with the addition of concrete ballast in the base there were no great problems in towing to site (see Figure 9). Mooring was relatively simple, although we did have some problems at the buoy's particular location as there was a fairly high tidal flow of about 4 knots which produced considerable drift. The telemetry system for signalling results ashore had five channels: these facilitated the measurement of the water levels adjacent to and within the buoy, its vertical heave motion, and the rotor's torque and velocity.

It would be useful to draw some general conclusions about the overall device. One of its attractive features is that it is very simple; there is really only one moving part which is well removed from the water surface so it could readily be protected by means of a suitable cowling. In addition it is a modular system which should allow ease of access for servicing and installation of supplementary equipment. The modular construction should lead to mass production and reduce construction costs. The fact that the system works better with flexible moorings would again alleviate problems that are associated with moorings. The structural form is spherical which is an ideal form of construction for withstanding the high forces at sea. Alternatively a cylindrical structure with a conical transition to the neck could be adopted for ease of fabrication.

DISCUSSION

D M Sharp (British Ropes Ltd)
Two questions to Professor Long: what water depth were you involved with in this device? And what exactly do you mean by flexible moorings: is it long catenary moorings, or moorings of low elasticity?

Prof A E Long
We have considered a possible prototype device of the order of 25 m in diameter, in about 50 m depth of water, which would occur something between 5 and 10 miles offshore. We feel that there is possibly a need for some radically different thinking as far as moorings are concerned so that you get horizontal or to some extent horizontal mooring systems which have a high horizontal compliance and also almost complete freedom to heave. We have considered a possible linking system of a number of the buoys along a line, which could then be end-connected to a fairly rigid system.
Thus far you have seen wave power through the eyes of different device teams, seeing the results of their work in developing devices from small-scale tests through to bigger tests and then to their first ideas of what their devices might look like at full-scale. Part of our brief as consultants to the Department of Energy on wave power has been to take an independent look at these devices at full-scale, to see:

- how well they work
- how well they would survive in real conditions out in the Atlantic
- how they might be built (the facilities that are available in the UK, the resources that will be available for building them)
- how much they might cost
- and finally how much power they might produce.

Our brief, then, was to produce a global assessment of the devices and of wave power, in the context not of a single device but of a large-scale power installation for the UK. In fact as our brief we have taken initially a 2 GW rated installation. I am now going to talk for a little while about this work.

At the outset let me sound a word of warning. This is the first bringing-together of all the work that has been done since the start of the UK programme to try to show the whole picture as it relates to the first-generation devices. The device teams themselves have told you how uncertain their own thinking is in some areas. Tomorrow the leaders of the Technical Advisory Groups will be telling you that in some of their areas work also is still at a very early stage. The composite which we are now presenting has all these uncertainties built into it; but we believe that the broad picture that we are presenting is nevertheless a very valuable one.

First of all what might a large scale wave energy scheme for the UK look like? Figure 1 shows the UK with the sites for wave power stations marked on it for a mean annual output between 3 GW and 9 GW. If you have noted the energies quoted for the sea and the efficiencies of devices, you may be surprised that we need so much sea space for the power quoted. The reasons for this are fairly straightforward. In addition to dealing with the efficiency of the devices themselves we also have to deal with the effects of directionality which Dr Clarke mentioned this morning; when the sea is running north-to-south and the devices are facing west it is difficult to get very much energy out of the sea. Then we have to allow for the gaps between the devices; we can't put a continuous wall around the coast. We have to leave room for fishing boats and for moorings. Devices are on compliant moorings and must be far enough apart to prevent them colliding with one another in rough seas. Then we must allow for power which is lost along the way from the prime mover to the grid. Overall we find that we do require this space in order to tap the resource.

Figure 2 shows part of the scheme at a larger scale. Scotland is a favoured location because of the sea energy which is available. The figure shows four 500 MW stations; there are spaces for navigation and gaps between devices determined by the moorings. Electricity is transmitted via 22 kv AC cables from the devices to collector stations which are mounted on small offshore platforms, and then via 250 kv DC links to Uist and on to the main line terminal. The lines to the present centres of use are long; this is inevitable. The alignments that we have shown in Figure 2 are completely notional; nobody has applied for planning permission or anything like that.

Figure 1

THE SCALE OF A POSSIBLE COMPLETE NATIONAL WAVE POWER SCHEME
- MEAN ANNUAL OUTPUT BETWEEN 3 AND 9 GW

Figure 2

I should perhaps refer very briefly to environmental influences. They are not, I think, of governing importance but we should note some points. The devices themselves are low in the water and distant from the shore and present no visual problems. Transmission lines are transmission lines and we all
They will be long-term, not short-term; there will be local
these devices against the largest waves, we have to let the
more efficient use of sea space, so as not to lose too much
device go to and fro, and just hold it against the mean force.

Figure 3

While the mean force is 20 m/sec², we must consider that

The slides you have seen so far from earlier speakers have
been of 1/100th scale models and 1/10th scale models, but
the engineer has to face the problem of the full scale device;
here, Figure 5, for which I’m indebted to my colleague John
Dawson, illustrates the problem. We have to apply Froude
scaling and by way of illustration we decided to apply it to a
mouse, which we scaled up by a factor of 100, which is a
large forces and slow motion. These are two things that
classify the energy which we are trying to
extract. Taken together, large forces and slow motion lead
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typical ratio between our tank models and real wave energy
devices. You finish up with an elephant-sized mouse. We have
taken a close look at part of a wave power scheme, Figure 3 shows about one mile of a wave power station. We
have picked here the NEL device just for convenience. Each
device is about 116 m long. The sheer scale of the mooring
problem is obvious. The moorings of individual devices
overlap. This has been done to close the devices up and get a
more efficient use of sea space, so as not to lose too much
energy through the gaps. We are searching therefore for
economical methods of mooring on rock bottoms. We are
looking for mooring systems which provide the compliance
which is necessary; because we can’t possibly hold one of
these devices against the largest waves, we have to let the
device go to and fro, and just hold it against the mean force.
Yet at the same time we have to have a mooring system
which is sufficiently stiff not to allow adjacent devices to
bump into each other; it sounds simple, but in fact is not at all
simple. The installation of these devices will be fairly easy in
some areas and much more difficult in others. We think it
shouldn’t be too difficult with floating devices on installed
moorings. On the other hand installing something like the
HRS device involves placing caissons on an open Atlantic
coast, and that is a very real problem which many civil
engineers will worry about a great deal.

Figure 4 shows some of the constraints on wave power. First
of all it simply illustrates the order of energies which are
available to us from various renewable sources. Wave energy
is shown at about 2 kW/m²; this is a very arbitrary sort of unit
which we obtained by taking the energy available of about 33
kW/m and dividing it by a depth of 16 m (a number of the
devices have a working face of the order of 16 m). We thus
finished with a figure of 2, but it could have been a figure or 3
or 4 quite as easily for a different device. This is simply to
illustrate that we are dealing with low power density here.
Given this low power density as one problem we also have
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COMPARISON OF POWER DENSITIES.

<table>
<thead>
<tr>
<th></th>
<th>Solar - Annual Average</th>
<th>Wave Energy - Annual Average</th>
<th>Wind - Annual Average</th>
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<td>2.0 kW/m²</td>
<td>1.0 kW/m²</td>
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</table>

LOW POWER DENSITY

- LARGE FORCES
- SLOW MOTION
- LARGE DEVICES

STRUCTURAL PROBLEMS

MECHANICAL PROBLEMS - A SPEED-UP SYSTEM IS NEEDED FOR POWER GENERATION

FEASIBILITY COST LOGISTICS

THE PROBLEMS ARISING FROM THE LOW POWER DENSITY OF WAVE POWER

Figure 4

APPLY FRRODE SCALING TO A MOUSE, FOR THE DESIGN OF A NEW ELEPHANT.

Figure 5

<table>
<thead>
<tr>
<th>SCALE FACTOR</th>
<th>MOUSE</th>
<th>NEW ELEPHANT SIZED MOUSE</th>
<th>COMPARISON WITH FIELD TESTED ELEPHANT</th>
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<td>2000 kg</td>
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<td>20 m/s - 50 m/s</td>
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<td>20 m/s²</td>
<td>10 m/s²</td>
</tr>
<tr>
<td>ACCELERATION FORCE</td>
<td>100000</td>
<td>0.2 - 2.0 m/s²</td>
<td>40000 - 40,000 m/s²</td>
</tr>
<tr>
<td>MEAN STRESS IN LEGS</td>
<td>100</td>
<td>0.2 N/mm²</td>
<td>20 N/mm²</td>
</tr>
</tbody>
</table>

PROBLEMS IN THE DESIGN OF LARGE MOVING BODIES

Figure 6

THE RANDOMNESS OF WAVE POWER

Figure 7

The result of all this randomness is that there is a very marked variation of the power which is actually available to the device. I mention this because current generating machinery - turbines, pumps, generators - was simply not designed or even conceived for the sort of random duty which is a feature of wave power. As Jim Platts pointed out this morning, the structures that we are dealing with have to be able to survive power measured in megawatts when what we are really trying to do is to take out power which is measured in a few tens of kilowatts.

Figure 7 lists the constraints imposed by the environment in which we are operating. Weed may be a significant problem in a device such as the HRS rectifier. This aspect is simply not known, but there is some concern that weeds growing into valves might be a difficult problem. Material durability, corrosion fatigue and wave forces are relatively well researched problems associated with this hostile environment. It is possible to get materials which are very good in water, but we are looking for something much more: elephants don't look like mice. This is meant to make the simple point that the problems which are trivial on a model can loom very large and sometimes be insuperable at full-scale proportions.

A further set of engineering constraints is associated with the randomness of wave power. At the top of Figure 6 we see the variation of power month-by-month over the year. Lower down we see the distribution of power on an hourly basis; the probability of occurrence for each possible power level. This can be expressed differently by the scatter diagram of the sea states within the year. The third section of Figure 6 shows the variation second-by-second of the surface elevation of the waves. The bottom section shows the variation of the power level. Generally speaking we got two power cycles for each wave, (for example, for a device that puffs air there is a puff on the crest and a puff on the trough). The result of all this randomness is that there is a very marked variation of the power which is actually available to the device. As Jim Platts pointed out this morning, the structures that we are dealing with have to survive power measured in megawatts when what we are really trying to do is to take out power which is measured in a few tens of kilowatts.

Figure 7 lists some problems associated with the remoteness of the location. The impact of construction and installation on the local economy is probably wholly good as far as local people are concerned. Out at sea we are dealing with problems of inspection, maintenance and repair; the access problems are of a different order from those in a land-based station. The transmission of the power to the grid is over quite a long distance. The power is economically more attractive to users in the Hebrides than to users in the south of England or even elsewhere in Scotland.
That covers some of the constraints which affect the design of wave power stations: they are quite severe constraints and present a challenge to be overcome. Now I turn to specific devices, to comment on some of the attractions and the problems that each presents to the engineer.

Figure 9 is a simple isometric of the NEL device, cut away to show internal detail. It is 116 m long, 35 m deep, 35 m wide, (virtually square in section). It has the attraction that it is a monolithic structure; one might even say it is a chunky structure, and this is extremely good from the point of view of survival. Structural loadings on this device present no problems to the structural designer. The power conversion is straightforward. As has already been explained, an air turbine is a very good way of moving from a high force slow speed into a low force high speed situation. The main problem presented here as far as the engineering is concerned is that at present in this device the power comes in a lot of separate little parcels, one to each cell as it is presently devised, and combining these into 'clean' electricity presents certain additional costs in the design. Building the device is perhaps the largest problem. A large dry dock construction facility is required. The bottom half of the device must be built first in the dock, then floated out; the rest of the structure is added in adjacent deeper water. Mooring it presents problems: it seems to have rather large mooring forces but I will not comment further on this because mooring forces are not yet well investigated.

Figure 10 shows the Cockerell raft. It is 100 m long in total, 50 m wide and 7 m deep; those of you who follow football will be able to see it roughly in terms of a football pitch. It is relatively easy to construct as the designers, Wavepower Ltd, have indicated and its shallow draft means that it can be built anywhere. However it is a large structure, with a large area of rigid working surface which inevitably has cost associated with it (coming back to the point which Prof French was making a few minutes ago). It is an articulated structure which means hinges. The design illustrated was the design in June, but the layout has changed significantly since. The designers are now favouring one row of hinges rather than two, and a distributed line of hinges rather than the two very large hinges shown in Figure 10. Each of the hinges shown is about the same size as the large hinges which support the 60 m Thames Barrier gates. If we go to smaller hinges, then the hinges come cheaper but we may have problems of alignment. The power conversion of the June design has a lot of moving parts, which tends to make it expensive. The problems of mooring, with a need for compliant moorings and yet small gaps and no collisions, have already been described by Wavepower Ltd.

Figure 11 shows the HRS design. This has significant attractions, with a conventional power take-off and energy storage for smoothing. It is good for power gathering and onward transmission because it is a fixed device. One of the problems of floating wave devices is getting power back to land down flexible cables, which tend to be expensive and present reliability problems. If the device is fixed, power collection is much easier; maintenance and access are also easier. However, this device also has problems. There is a limited choice of sites on which it can be built. The problem of weed I have mentioned. Installation problems might arise because the device is a bad ship, and probably it has to be floated into position as a large caisson. The design has a double bottom to give torsional strength but this has added to the structure cost. As an impounding reservoir it is highly inefficient, in the sense that there is a very long 'dam' containing a very small volume of water. This tends to be an inherent feature of the device, resulting as it does from the
need to have alternating inlet and outlet compartments, and so far no viable alternative configuration has been found. Wall thicknesses in most wave power devices are between 1 m and about 0.3 m: the HRS rectifier has wall thicknesses at the top end of the range (about 1 m), the thicknesses being mainly determined by the differential hydrostatic head within the device.

Figure 12 shows the Salter duck. This device is an elegant concept which has very good interaction with the waves. The ducks are very clever at using the small waves and ducking the big ones. Theoretically the efficiency is high and mooring forces are probably low. On the other hand the spine brings us right back to the problem of the elephant-sized mouse. The spine simply does not scale up; or rather, there is no full-scale engineering interpretation: there is no material available which meets the requirements of high strength and low modulus. You saw earlier that one solution is to aim for a composite spine, which tends to be very expensive and raises other difficulties. So there is an engineering problem here which is not yet solved. The power take-off has also proved extremely difficult and there is as yet no solution which anybody is really happy about. It is an extremely difficult problem to take power off from a sleeve rolling round a way or another. The structure is 193 m long with a width of only 6.3 m and a maximum depth of only 17 m.

Figure 14 shows the Wells device. It has no moving parts and was specifically intended to exploit the point absorber effect; it is unfortunate that the characteristics which were expected of point absorbers, (very high efficiencies deduced theoretically from linear hydrodynamics theory), don’t actually appear to be realised when we move into the non-linear regime of real power waves. We know that the device efficiency in working seas is not as high as had been hoped. This device has not yet been costed.

Figure 15 shows the Vickers device. No significant design work has been done on this device and it has not been costed. It shares with the HRS device a fundamental problem of too large a structure for the power captured. The device contains a large volume of air and a large reservoir of water; hence it is a large and potentially expensive structure.

Our brief was to report to the Department of Energy, making a comprehensive assessment of devices and of wave energy. The criteria we used were:

- feasibility, at a reasonable cost
- effectiveness of the device (the amount of power it produces)
- capital and running cost
- the size of the total UK resource (applied to assessing wave power as a whole rather than individual devices).

Figure 16 indicates the main components of the feasibility criterion. The majority can be quantified automatically; they affect the cost of the reference design or the output. But some

Figure 13
considerations don't come through so clearly in the numbers. Consider the structure. We are assessing for survival, the problem we mentioned specifically in relation to Prof French's device. Will a device survive; is it durable; will it wear out or corrode; how easy is it to construct and install (particularly applicable to the HRS device)? Consider fatigue. In some ways wave power devices are more difficult from the point of view of fatigue life than other offshore structures. An offshore oil platform structure is designed to resist the 100-year wave, which tends to give it a reasonable resistance to a whole spectrum of smaller waves; but wave energy devices are designed, where possible, to ride the large waves, and may well be fully stressed by the more modest waves in the spectrum which have a high number of occurrences in the life of the structure. In such a device fatigue considerations will dominate parts of the structure design.

Mechanical efficiency presents problems on account of the highly varying loading on the plant. For instance, the NEL turbine has to accept air a puff at a time, and there isn't as yet a turbine which has been designed from scratch specifically for this sort of duty. Access for maintenance is a big problem for the duck with machinery in a difficult confined space. There is much to be considered here but we haven't time to go through everything in detail. My aim has been to show you that we have tried to take into account all aspects of feasibility.

Another criterion we had to apply was device effectiveness; its power output into the grid. We had to be able to describe the power output in detail and we therefore needed a model of the whole power chain. This meant considering and quantifying as far as possible:

- the reliability of the system and its components
- the efficiency of the system and its components
- the output of the primary converter (which is the input to the system).

The system which transmits the device output to the grid is shown schematically in Figure 17. From devices power is led through AC flexible cable under water to converter stations on platforms where power is collected and converted. It then goes through a DC submarine cable link to shore and on to Skye. An overhead DC link takes it across Skye to mainland inverter stations. The whole of this system has been designed. Before we can cost anything we have to design it. The design includes link cables between adjacent collector platforms to provide some degree of redundancy to allow for failed cables.
The second case shows the distributions at the end of a no-repair period, when there have been massive storms and it has been impossible to get at anything for a four-month period. One of the inputs to this analysis is shown at the bottom of Figure 18, which shows a plot of the probability that a device isn't operating, as a function of time-of-year. The numbers plotted (rising to a peak of 15%) are conjectural but the concept is valid.

Figure 19 displays the results of this analysis from a different point of view. Here the power input to the system from the devices varies, and the graphs show the average proportions of output power that would be lost because of failures in each group of components. The big losses at the upper end of the scale arise because of failures in the submarine cable links. Component failure leads to a high level of power loss in the system as a whole.

![Diagram showing power loss in various components of the system under different load conditions.](image)

**THE AVERAGE POWER LOST IN VARIOUS COMPONENTS OF THE SYSTEM UNDER DIFFERENT LOAD CONDITIONS**

**Figure 19**

Figure 20 shows some aspects of the sea climate. Data of this type forms the basis for assessing the primary device productivity. The upper part of the figure shows the scatter diagram for the reference climate based on measurements at South Uist in 1976-77. The lower left-hand part of the figure shows the directional distribution, the proportion of wave energy coming from each of the different points of the compass. As no measurements are available for South Uist we have had to make do with predictions derived using the Meteorological Office simulation of the North Atlantic. The last part of the figure has been derived from the directional distribution and shows the energy which is available for capture by lines of devices moored at various angles. The best direction is facing just south of west giving 65% energy available.

Finally, Figure 21 contains a simplified flow-chart showing the structure of the power output model. The model can use a number of different inputs. In some cases lack of suitable data has so far made it necessary to adopt simplifying assumptions. The main model inputs are:

- wave climate data
- data on device efficiencies (from laboratory tests in mixed or monochromatic seas)
- device size (which can eventually be optimised)
- data on efficiencies of the elements in the power chain.

The model calculates the resultant power outputs and can display them in a variety of ways.

Figure 22 shows an example of the application of the model for the oscillating water column device. The uppermost graph shows the laboratory data on device efficiency in monochromatic waves. The middle graphs show the efficiencies of the different components along the power chain from the device to the grid at Perth. All this data is input for the model shown in Figure 21, and the computer programme outputs the power produced at each stage. Further correction factors are applied to take account of the effects of directionality, site location, reliability, etc. The final results are given in the form of a predicted value, together with upper and lower 95% confidence limits. It is very difficult at the moment to know quite how reliable the figures are, and we have tried to estimate confidence limits for everything we have done. We may not have got them right but at least we have made a start. What I have been trying to describe very quickly is a relatively precise simulation model used with data which is not always as complete as we would like; in fact in some cases it is very incomplete data and the results can clearly not be better than the input data.

We have assessed the output of devices which are very much first-generation, which means that the results could be very misleading. For this reason we have identified three scenarios and tried to predict what might be the costs and productivity according to each.

- Scenario 1 relates to the current device designs, which are known not to have been optimised. It uses current technology with limited extrapolation in some areas. Estimates of cost are based on current production methods (though applied to producing very many devices on a large scale).
- Scenario 2 describes where we think we might get to with the best developments from the current designs. It is based on projections for refined, fully optimised designs. It makes optimistic assumptions about the use of new technologies (eg for intelligent power systems, improved transmission cables etc.). Costs are estimated assuming novel techniques for the mass production of heavy engineering components.
- Scenario 3 relates to as yet uninvited devices, constrained only by the inherent limitations imposed by the nature of the energy resource. If there is a single lesson from our work so far it is that we have to be in the business of new ideas and new ways of doing things. There is a strict limit to the tonnage of concrete that we can afford at these low power densities. Although it is strange to base a scenario on uninvited devices, this is a very real scenario.

Figure 23 shows the results of the output analysis for these scenarios. The incident average wave power of 30 GW, which allows for directionality effects, matches very well with the country's average demand of 28.5 GW, but at the moment the Scenario 1 output would only average 2 to 4 GW. We
think Scenario 2 might raise this figure to 8 GW. We haven't shown any estimates for Scenario 3 as we do not know enough even to hazard an intelligent guess.

Figure 24 gives the results of our costing exercise for wave power. These are the figures that Dr. Clarke mentioned this morning; the interest rate assumed is a Department of Energy norm. The life we have assumed for the scheme is, we think, distinctly conservative and this tends to balance the low interest rate and maintenance costs that have been used. Let me explain very briefly how we did the costings. We took the device teams' designs which you have seen today. The teams produced their own sets of engineering drawings and we completed any parts which were missing for any reason to produce drawings for costing; you can only cost something which can be put down on paper. We provided our own design drawings for the transmission links. We worked with three large contractors with experience of constructing for the North Sea: Wimpey (who have a construction yard at Nigg), McAlpine (with Ardyne Point) and Tarmac (who are part of the ANDOC Group). These three companies themselves put a lot of effort into developing methods of constructing the devices before doing their own costing. We used our own in-house specialists to get further costing figures on the plant side. Kennedy & Donkin used a similar procedure to cost the large mechanical and electrical components, using experienced contractors to do the pricing. We then applied upper and lower confidence limits to the results. Having done all that, there are very broad limits here; 20 to 40 pence per kWh. The reason why we don't want to be more exact than that is that although we can cost a set of drawings very precisely (though even that is difficult), the designs themselves are changing and improving so fast that costs which were produced last July wouldn't apply to some of the devices which you have seen today.

Figure 25 finally, shows the breakdown for costs for each device. In some ways this form of presentation can be mis-

---

Reference: Cambridge Scattering Diagram

SIGNIFICANT

--- UNIDIRECTIONAL WAVES ASSUMED

SPREADING FUNCTION COS + COS 2 ASSUMED

BREAKDOWN OF TOTAL WAVE POWER AS A
FUNCTION OF DIRECTION - MET OFFICE
SIMULATION NOV 77 - FEB 78

--- UNIDIRECTIONAL WAVES ASSUMED

SPREADING FUNCTION INCLUDED

PERCENTAGE OF ANNUAL WAVE ENERGY
AVAILABLE TO A LONG STRING OF DEVICES
AS A FUNCTION OF DEVICE HEADING

Figure 20
PROGRAMME FOR ASSESSMENT OF POWER LEVELS AND PRODUCTIVITY

STAGE 1 ANALYSIS

Figure 21

<table>
<thead>
<tr>
<th>PEAK POWER</th>
<th>TOTAL POWER</th>
</tr>
</thead>
<tbody>
<tr>
<td>IN GW HOURS</td>
<td>AVERAGED OVER YEAR</td>
</tr>
<tr>
<td>CURRENT GRID</td>
<td></td>
</tr>
<tr>
<td>CEBG</td>
<td></td>
</tr>
<tr>
<td>SSEB</td>
<td></td>
</tr>
<tr>
<td>INCIDENT WAVE POWER</td>
<td>ABOUT 500 GW IN STORMS</td>
</tr>
<tr>
<td>CURRENT WAVEPOWER DESIGNS</td>
<td>BETWEEN 12 GW AND 16 GW</td>
</tr>
<tr>
<td>SCENARIO 2 SCOPE FOR DEVELOPMENT</td>
<td></td>
</tr>
</tbody>
</table>

TOTAL UK WAVE POWER RESOURCE

Figure 22

Figure 23
ASSUMPTIONS-
INTEREST RATE = 5%
MAINTENANCE & RUNNING COSTS = 3% CAPITAL COST/YEAR
LIFE OF SCHEME = 30 YRS

<table>
<thead>
<tr>
<th>SCENARIO</th>
<th>CURRENT</th>
<th>WAVE POWER DESIGNS</th>
</tr>
</thead>
<tbody>
<tr>
<td>OSC. WAVE COL.</td>
<td>RAFTS</td>
<td>RECTIFIER</td>
</tr>
<tr>
<td>STRUCTURE</td>
<td>38</td>
<td>41</td>
</tr>
<tr>
<td>CONSTRUCT &amp; INSTALL</td>
<td></td>
<td></td>
</tr>
<tr>
<td>MOORING</td>
<td>31</td>
<td>11</td>
</tr>
<tr>
<td>MECHANICAL COMPONENTS &amp; ELECTRICAL GENERATION</td>
<td>10</td>
<td>24</td>
</tr>
<tr>
<td>POWER TRANSMISSION</td>
<td>4</td>
<td>6</td>
</tr>
<tr>
<td>OTHERS</td>
<td>18</td>
<td>17</td>
</tr>
<tr>
<td>TOTAL</td>
<td>100%</td>
<td>100%</td>
</tr>
</tbody>
</table>

% BREAKDOWN OF COSTS

Figure 24

leading, because with a lower cost device an element which is in fact well designed and low costs in absolute terms, may constitute a larger proportion of device total cost, with the implication that for this device this element is a weak point in design. This is the case with Prof French’s air bag.

Generally, structure costs predominate. Mechanical components are also expensive, although they tend to be less expensive for air turbine devices when compared with devices which have a large number of components in the power chain.

DISCUSSION

D MacGregor (Biarritz, France)
Would Mr Clark agree that the considerable use of storage of compressed air would help with the problem of randomness. A second question – could Mr Clark give his views on the question of security against possible enemy action?

P J Clark
I think air storage helps from second to second but not beyond that. The amount you would have to store to get rid of randomness on a longer time-scale is too large; but air storage is helpful from the electrical point of view.

H B Stansfield
If it is being used in connection with a hydraulic accumulator then you do need some air storage. Otherwise, using low pressure air in large volumes with high velocities air storage isn’t helpful.

J M Dawson
On the question of enemy action; if anyone wants to tow away 1000 km of wave power devices, he is welcome to try. Security of the cables is a more significant point as there won’t be nearly so many of those; but we haven’t studied it.

R Freer (Scottish Offshore Partnership)
I would like to ask Mr Stansfield about the size and number of the turbines. We heard this afternoon that for the HRS rectifier they spoke of variable-blade Kaplan turbines of 1 and 2 MW output. If the objective is to build 2000 MW in ten years that calls for the supply of a 1 MW variable-blade Kaplan turbine every day for the next ten years. Is this beyond the capacity of the turbine industry, and if it is can you give us some guidelines as to the minimum size of turbine we should be thinking about in these sets?

H B Stansfield
I haven’t looked into the logistics of supplying these things, but I agree with you that even getting half a dozen would take some time. There are finite limits to the production of stainless steel forgings and castings which are required for the turbine blades in a marine environment. Producing very large numbers might have to be a European endeavour extending outside this country. The minimum size of turbine depends on the actual rating of the individual device. In the case of the HRS you need a 1 MW which is a very large machine in fact.

J M Dawson
This is just another way of looking at the fact that current device designs would use up enormous resources. Eventually it all comes down to economics. We have not studied this in detail because it’s self-evident that at the moment the manufacturing capability just isn’t there. On the other hand, we must remember that for any large-scale scheme, completely new manufacturing capabilities would be set up, so we mustn’t be too conservative in assessing what is a reasonable number of turbines to produce in a year in the UK.

M J Platts (Wavepower Ltd)
Rolls-Royce produce thousands of turbines in a decade for a very peculiar environment out of most exotic materials; that’s the sort of production regime we ought to be thinking of for wave power turbines and other components.

P J Clark
We wouldn’t disagree with that.

H B Stansfield
Of course the Rolls-Royce engines you have in mind probably weigh about a tonne and a half. The turbines we are considering probably weigh something in the order of 15 to 20 tonnes. Their rotors are about 4½ to 5 m diameter, involving large stainless steel forgings and castings; it’s quite a different technology.

M J Platts
One can trade maths for complexity; I don’t think you are going to do the same quantity of technological work on stainless steel blades that Rolls-Royce do on their turbines.

P J Clark
We certainly agree with you that the setting-up of proper
Dr N W Bellamy (SEA/Lanchester Polytechnic)
I am speaking on behalf of the duck device team. Our first objective was not to minimise cost for this particular exercise; it was to prove the concept, and I think this has just about been proved as far the the duck is concerned. Our second objective was to solve the engineering problems. We are still in the middle of this; later on we hope to tackle the cost problem. If we do tackle the cost problem we might hope to reduce the cost of the device by a factor of 5. But there is still another factor of 5 to find, mainly in the transmission, load factor, reliability areas, which as a device team we can't do much about.

P J Clark
The question of reliability particularly depends on the integrity of undersea cables. These are debited with a lot of lost power to allow for their being taken up by fishing boats. If we put this size of investment into the sea we can't afford to keep losing it, but quite how we will avoid this I am not sure at the moment. Providing duplicate cables might be part of the answer, but longer term some definite restriction on shipping in the area may be required. We can't have people driving away with cables whenever they happen to want to put the anchor down. This is not an answer to your point, but simply a comment on one aspect you mention.

J M Dawson
Dr Bellamy's first point just illustrates that we have to consider concepts, engineering and costs simultaneously from now on and not in sequence.

G H Mellar (Centrax Ltd)
Earlier this afternoon Dr Butterworth showed us some very good photographs of the KaiMei wave barge and the Japanese air turbine. I realise that in June when Mr Clark was doing his report the UK had not yet decided to go ahead with the design. Based on what Dr Butterworth said this afternoon, could Mr Clark make an off-the-cuff comment on how this particular type of device compares with the devices he has already described?

P J Clark
We know quite a bit about KaiMei; it is not an unknown quantity as far as we are concerned. John Dawson was one of a UK group that visited Japan this year, and some testing has been done in this country.

R T S Baker (Sheffield Polytechnic)
Do the cost comparisons assume a current date or are they projected ahead to when the devices could be ready? Also, do the various assessments that have been given include or exclude the coasts of the south-west of England; presumably the transmission costs are different?

P J Clark
Costings are at 1978 prices. They are reported in that form to the Department of Energy who can use them for projections as they require. The costings relate only to a scheme off the Hebrides.

J M Dawson
The main change if we consider the south-west coasts is the transmission line. As the part that would have to be lengthened is not a very high component of cost, these costs are indicative of what the costs for the south-west of England would be. However, our costing has specifically been for a site off the Hebrides; resource figures definitely include all of the favoured UK sites as shown in Figure 1.
Yesterday you were presented with information on a number of devices being developed in the present programme, and heard that each is a critical item and a major cost item. The output of the device is, to say the least, raw, and requires conditioning in maybe several stages of conversion, which leave us with something useful miles from anywhere and hence requires transmission.

Devices cannot be assessed without considering the characteristics of the follow-up system and vice versa; so when a Technical Advisory Group was set up to look at generation and transmission systems it was recognised that there would be overlap and sometimes hard-to-reconcile pressures from each end. The group, TAG 6, has a membership shown in Figure 1; it includes representatives of the traditional energy industry equipment suppliers and potential users of wave energy product, together with ETSU and the Department of Energy to see fair play.

The aims of the group have been in two parts. First, to identify a wide range of possible generation and transmission options, and to submit them to comparative examination of feasibility, performance and cost: to narrow the field. Throughout this process, device teams have been free to consult members of TAG 6 for design information and, more importantly perhaps,
to impose device-oriented constraints on our programme.

The second part is to assess the effect of generation and transmission system characteristics on the performance, operational characteristics and economies of particular devices, and to estimate the R&D effort and timescales needed to implement particular designs. TAG 6 also has to keep WESC generally appraised of the state of developments in this area.

The first objective, identifying systems, led to a very wide choice which is displayed in Figure 2. At the device end there were many detailed options for primary and secondary conversion. Transmission could be thermal (as heated water or oil), hydraulic, in a chemical form, or as most of us have assumed as electricity. End-use could equally be as chemicals or as electricity, or the substitution for some other energy-intensive activity, as in district heating or power station feedwater heating, for example. These transmission and end-use areas are truly generic, and we will deal with them first.

Thermal transmission, with heat generated by a brake, is both the simplest and the least promising route considered. The main advantages and disadvantages are summarised in Figure 3. The cost of handling water is high, the end product is of very low grade in energy terms, and none of the possible uses could stand the high cost (based on very optimistic device cost assumptions) even when the opportunity is assumed to exist.

The main points on hydraulic transmission are summarised in Figure 4. It would almost certainly have to be associated with electricity production, but does have the major advantage of getting all the electrical equipment on shore. Although the developments in the North Sea make both pipelines and the necessary flexible couplings feasible, the cost is very high - even with seawater pumping which allows transmission using only a single pipeline. Long distance hydraulic transmission was therefore ruled out, although short distance connections between devices and large generator units at sea continue to be of great interest in those systems where hydraulic primary conversion is inevitable.

Concepts of the hydrogen economy, the anticipated need for synthetic hydrocarbons and ammonia (for fertiliser) suggest that these potentially valuable chemical energy carriers might improve wave power economics and bring operational advantages. In each case the feedstock is hydrogen, which means that electricity still has to be produced on or near the wave energy device; but storage and transmission are now

<table>
<thead>
<tr>
<th>TRANSMISSION OPTIONS 1</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Thermal</strong></td>
</tr>
<tr>
<td>- Simplest and feasible</td>
</tr>
<tr>
<td>- Cost (excluding WEC) not small (could supply 130°C water at 26p/therm)</td>
</tr>
<tr>
<td>- Uses limited to</td>
</tr>
<tr>
<td>- District heating - not likely at wave power locations</td>
</tr>
<tr>
<td>- Power station preheat - as above</td>
</tr>
<tr>
<td>- Generation of electricity - low efficiency hence very high costs</td>
</tr>
<tr>
<td><strong>NOT WORTH PURSUING</strong></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>TRANSMISSION OPTIONS 2</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Hydraulic Pipeline</strong></td>
</tr>
<tr>
<td>- Most applicable to devices with hydraulic power take off - ducks/rafts</td>
</tr>
<tr>
<td><strong>Advantages</strong></td>
</tr>
<tr>
<td>- Enables all electrical equipment to be shore based</td>
</tr>
<tr>
<td>- Is technically feasible at up to 80 MW using North Sea oil technology</td>
</tr>
<tr>
<td><strong>Disadvantages</strong></td>
</tr>
<tr>
<td>- Only use is electricity generation, i.e. only replaces cable</td>
</tr>
<tr>
<td>- Cost, concentrated in pipe, laying and protection, is high ~£560/kW for 24 km</td>
</tr>
<tr>
<td><strong>ALTHOUGH MAIN TRANSMISSION NOT OF INTEREST, INTER-WEC HYDRAULIC CONNECTION IS INVALUABLE</strong></td>
</tr>
<tr>
<td>- Could incorporate substantial smoothing</td>
</tr>
<tr>
<td>- Filtered sea water preferred to oil (pipe length, losses, cost of fluid)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>HYDROGEN</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Advantages</strong></td>
</tr>
<tr>
<td>- Freedom of WEC siting</td>
</tr>
<tr>
<td>- Easy energy storage</td>
</tr>
<tr>
<td>- No fixed link to shore</td>
</tr>
<tr>
<td>- Electrolysers tolerate energy input variations</td>
</tr>
<tr>
<td>- Technical feasibility limited only by WEC mechanical design</td>
</tr>
<tr>
<td><strong>Technology Preferred</strong></td>
</tr>
<tr>
<td>- Electrolysis using</td>
</tr>
<tr>
<td>- On board desalination</td>
</tr>
<tr>
<td>- Piped gas (loss of freedom) or</td>
</tr>
<tr>
<td>- Tankered liquid</td>
</tr>
<tr>
<td><strong>Cost</strong></td>
</tr>
<tr>
<td>Based on very optimistic wave generated electricity costs and advanced electrolysers:</td>
</tr>
<tr>
<td>Piped gas = 1.4p/kWhTH (41p/therm)</td>
</tr>
<tr>
<td>Tankered liquid = 1.8p/kWhTH (53p/therm)</td>
</tr>
<tr>
<td><strong>EITHER &gt; 4 x FOSSIL FUEL COSTS</strong></td>
</tr>
</tbody>
</table>
AMMONIA
- ETSU study indicates ammonia to be a potentially valuable product
- BUT even on optimistic wave energy assumptions.
- Minimum cost ~2 x production from coal

SYNTHETIC HYDROCARBONS
- Minimum cost exceeds 2 x production from coal even ignoring the cost of providing the carbon

THERE IS LITTLE PROSPECT FOR HYDROGEN OR ITS DERIVATIVES BEING WORTH CONSIDERING FROM WAVE ENERGY

have reached this conclusion. As realistic device costs are included, economic considerations will count even more heavily against the hydrogen approach. With an expensive feedstock it is hardly surprising that ammonia and synthetic hydrocarbons (summarised in Figure 6) are also likely to be priced out of the market. The cost compared with production from coal is based on a wave power electricity cost of only 1p/kWh. At this level its use as electricity would be preferred.

Electrical transmission, including submarine cabling, is well-established technology and, although not without problems (especially those created by trawlers and other seafarers), is both cheap and efficient. The main points are summarised in Figure 7. Even the novel area of flexible connections to the moving wave power device appears tractable, although power transfers will be limited to 2 to 15 MW per cable, depending on whether transmission is at generator or a higher voltage.

The choice is clear: unless we have to be free to site WECs unmoored and at very large distances from shore, electrical transmission is preferred. The market exists, the technology is clear, and the costs should be reasonable. At this point we have to move into the overlap area and consider how the device will deliver its power, and how that can be matched to the electricity supply system.

For compatibility with other generating plant, it will be necessary to provide reasonably smooth power at 50 Hz. Normal plant experience and economic considerations also insist on high load factor operation of what is a high cost energy source, and that the system should be as simple, reliable and maintainable as possible with the highest overall efficiency. For preference it should be controlled from shore in units of 200 MW or so, but wave energy is random, variable, low frequency power at low energy densities, and is a far cry from that ideal.

The distribution of power and the wide variation of input sea states are well understood. Target ratings to satisfy the load factor requirement need to be in the 50 to 100 kW/m range, leading to WEC units with little more than 2 MW maximum continuous rating. These figures are based on India data, but the results are readily scaled to conditions at other locations. We have also noted that power swings are rapid (for which the system needs to be self-regulating), and that with very persistent calms lasting several days even in winter, long-term storage is not an economic proposition. Fortunately storage is unlikely to be considered necessary so long as wave power or one of the other renewables does not exceed 20% of the generating system peak demand. Short-term storage, on the other hand, could be essential to smooth second-to-second and minute-to-minute variations.

Short-term variations are even more worrying (see Figure 8). A typical, very average wave (Figure 9) leads to a very similar device velocity response (Figure 10) when the device is linearly loaded - the device team's ideal. The resultant power (Figure 11) is very peaky - this being a mere 3 minutes of

SHORT TERM VARIATIONS
- An individual wave record shows large variability in instantaneous power
- To achieve the average power, \( \bar{P} \), ratings up to 10 \( \bar{P} \) would be needed
- Cost of 500 kW/m equipment for 50 kW/m maximum continuous rating prohibitive

DEFINE WEC RESPONSE
- Wave statistics are known
- For linearly loaded devices WEC velocity is Gaussian
- Power output statistics then easily determined and we can define
  - the effect of power limiting on output
  - estimate lifetime velocity distributions
  - estimate distributions of torques/forces involved in power transfer
output. Note especially that the peak power levels are around 10 times the average: clearly it will not be economic to cater for this in generation and transmission equipment.

The effect of restricting the power level is readily estimated from the known output statistics; the result is plotted in Figure 12. Setting too low a limit is very wasteful, but three times the maximum continuous rating will allow conversion of up to 90% of the maximum in most circumstances. A combination of this control and WEC characteristics leads to a significant levelling of output power, through a progressive reduction in overall efficiency as the input power increases beyond the design level. Figure 13 show some examples of this: the input power ranges from 16 to nearly 2000 MW on average, and for two sizes of rafts the output power is controlled within very much narrower limits.

A worrying consequence of WEC response and of this type of control is excess device motions; overspeeds of 4:1 or more on rated output being experienced by all devices. This overspeeding and the associated displacements and accelerations, limited only by hydrodynamic non-linearities, is a major equipment design parameter and of great significance for ducks and rafts (see Figure 14). Electrical machines are impractical at device speed and speed increase is essential. The main points are summarised in Figure 15. Direct gearing is not possible because of the high inertial loads and overspeed conditions. Hydraulic pumps and turbines are necessary for both devices. Once in use, hydraulics allow considerable freedom to choose machine speeds and the speed ranges can be minimised by storage and diversity in a long hydraulically interconnected WEC system. Examination of alternative generator types and control requirements led us to a strong preference for AC synchronous machines — even though they are most unlikely to be synchronised with the grid.

The preferred electrical transmission system summarised in Figures 16 and 17 can be applied to all WEC systems. It
ELECTRICAL MACHINES

Device Speed (duck/raft)
- Not feasible; high weight and cost
- Minimum rated speed 100 rpm

Geared
- Reversing loads excessive, hence need for hydraulics in duck/raft systems

Likely Drive Characteristics
- Synchronous at up to 3000 rpm
- More likely varying speed over a range limited by store and diversity of supply

Machine Suitability
- Permanent magnet – for excitation only
- Fully compensated separately excited DC machines – suitable only for local loads
- Induction generators – robust but limited efficiency with no cost advantage over:
  - AC synchronous – best choice for flexibility in application, efficiency and cost

![Figure 14](image)

comprises generation of AC at an arbitrary frequency varying from machine to machine, each with locally controlled field forcing. Flexible cables link single or connected groups of generators to either sea bed or platform mounted transformer/rectifier modules which are series connected into an HVDC main transmission to shore. When power levels allow, the transformer may be transferred to the WEC. Power demand is matched to the wave input through control of the demand current at the onshore inverter station. Operation and control of the offshore equipment is automatic. An overall smooth output of 200 MW or so is achieved through a combination of local storage and diversity, shown very simply in Figure 18, with connections between adjacent systems being possible in the hydraulics, on the WEC by coupling generator outputs or finally in the concentration of individual outputs into the main HVDC power cable to shore. The sooner this smoothing is achieved, the cheaper the system – within bounds. This conveniently brings us close to the

![Figure 15](image)

PREFERRED ELECTRICAL TRANSMISSION

- A single system concept which can be universally applied has been identified:
  - synchronous AC machines with locally-controlled field forcing
  - flexible cable to sea bed or platform mounted transformer/rectifier modules
  - series connection of modules to main HVDC cable to shore
  - on shore inverter station providing AC to grid and overall power control (by current demand)

- Scheme relies on modules of 200 MW being substantially smooth by virtue of diversity and limited storage

- Sensitivity to transmission distance not great – add ~3% to cost per 20 km addition (unless adverse ground conditions encountered)

![Figure 16](image)

![Figure 17](image)

We start with ducks and rafts which from the generation and transmission viewpoint are generically similar. Here we have massive moving structures and power extraction from their relative motions. The very low speeds lead to extremely large forces and several conversion stages are required. Gearing or mechanical-to-hydraulic speed increase is essential and storage or smoothing through diversity is also required. Because hydraulics seem inevitable, but require smoothing, the device team ideal of a linear load is not simply achieved. High frequency switching of many parallel rams is possible but, from a reliability standpoint, very undesirable. Hydraulic storage in normal accumulators, we have found, is extremely expensive and may account for £500/kW alone and therefore the maximum use must be made of diversity. The duck spine
concept is ideal for this. For the raft, either flexible links or the 'spine type' alternative shown in Figure 19 will be required, and you will have noted yesterday that that particular device team is moving its thinking in exactly that direction.

Mechanically ducks are a major worry. The very small working space at a large diameter which the spine necessitates means that only axial ram pumps and cam tracks or novel gears can be employed to transfer load to the rotating hydraulic pumps which all are agreed are inevitable. The ram pumps are the most direct and simple drive which are capable of providing the load and meeting the stringent space requirements for the duck and duck spine. These devices need proving, however, especially in the cam/cam follower area. If we choose to use gears, the tolerances which must be achieved will require a novel design in which the pinions are free to follow the undulations which are inevitable in the outer gear ring, but again it is just credible. A worry, however, is that cam followers and gears will require a very carefully controlled environment if they are to achieve any sort of life – which leads to a need for reliable seawater seals at duck diameter and good oil lubrication. It is not clear that a suitable drive can be engineered.

Rafts, on the other hand, are more likely to succeed since they have a great range of power take-off options (including geared ram pumps, low head seawater vane pumps, and crank-driven rams), good access for maintenance and a better controlled machine operating environment. Bearings may be difficult in oil with the present device team design because of the large number of seals involved. The large excursions in extremes are a worry but the device team is making good progress towards solving this problem as we heard yesterday.

Direct hydraulic devices like the HRS rectifier and the Vickers underwater design give us a number of benefits: built-in storage, direct conversion by a turbo-generator, and no requirement for flexible cables. A problem is that the very low heads mostly less than 4 m, lead to very large slow turbines and very high costs (£400-600/kW for the turbines alone). In the scale of things this can be offset against the cheapest, most efficient and possibly synchronous transmission. With somewhat higher heads, from a different but fixed device, this is a very attractive route.

The remaining generic group are the air turbine devices, NEL’s oscillating water column, the Japanese KaiMei, Queen’s University’s air buoy and French’s air bags. These have all the advantages of the direct hydraulic systems but with smaller, cheaper and faster turbines. The advantages are summarised in Figure 20. Local storage is now relatively straightforward using flywheels and, uniquely, the power conversion equipment can be concentrated in relatively manageable and accessible modules. Existing turbines cannot cope with oscillating air flows and flap rectification is required but several self-rectifying designs are being investigated, including the particularly simple Wells turbine described yesterday by Prof Long. Not only is the device remarkably simple, but CEGB theoretical studies have indicated a high efficiency potential (see Figure 21). With the turbine’s unusual design, it self-starts; on a cyclic flow it will indeed achieve high-speed unidirectional rotation. This is one of several conventional and novel turbines now being developed by NEL, GEC and CEGB in support of what appears to be the best
NEEDS OF CONTINUING PROGRAMME

Generic
- Study seals, bearings, gears and hydraulic systems to improve chances of duck and raft systems
- Hydraulic links for rafts
- Flexible and main cables and outline routing studies
- Site investigations and relationship to CEGB and Scottish systems
- Submarine and platform-mounted transformer/rectifier modules
- Assist in air turbine assessments

System Modelling
- Examine control, stability and performance of WEC-generator-transmission systems in detail
- Examine reliability and maintenance aspects of device teams’ designs

Economics
- Estimate component and system costs
- Examine economics from the customer viewpoint

ALL THESE ACTIVITIES REQUIRE A WELL-DEFINED DEVICE SPECIFICATION
EFFICIENCY OF A DEVICE WITH SIMPLIFIED HYDRAULICS

Figure 25

A SIMPLE HYDRAULIC CONTROL STRATEGY EMPLOYING THREE FIXED TORQUE LEVELS

Figure 26

WAVE POWER kW/m

1 2 3

EFFICIENCY OF A DEVICE WITH SIMPLIFIED HYDRAULICS

Figure 25

A SIMPLE HYDRAULIC CONTROL STRATEGY EMPLOYING THREE FIXED TORQUE LEVELS

Figure 26

Environmental effects, abrasion and corrosion, plus installation and maintenance studies and fatigue tests. Figure 27 shows cross-sections of a flexible cable and a rather inflexible HV DC cable of, it will be noted, 25 times the rating. Flexible cable is expensive (per kW km) and we are investigating the relative merits of platform and sea bed mounted transformer-rectifier modules - a first cost versus feasibility reliability and maintenance trade-off. The fatigue tests will be conducted on samples of a number of flexible cables in a cold pressurised seawater environment under full electrical stress; something like 6 million 35° cycles per year are planned in these tests.

On system modelling, we are constrained only to analyse well-defined systems and apart from advice to device teams only air turbine system studies are proceeding at present at IRD. The model includes the device, turbine, flywheel storage with a variable time constant, the generator and its control and the interconnected system. The work involves real-time random wave simulation and following the response of each element of the system in detail. A typical air flow record, shown in Figure 28 for a rectified turbine of the NEL preferred type, reflects the wave input very directly because of the inherently linear air turbine load characteristic. With a small value of inertia to store about 5 secs of rated output, the turbine speed varies between 500 and 110 rpm and with a fairly simple control philosophy (see Figure 29). The terminal voltage (shown in Figure 30) also varies down to 50 to 60% of the peak, but a truly diverse system of this type should easily achieve less than 5 to 10% low frequency ripple per 200 MW line, and less as the installed system is even larger.

An area which is taking on ever more importance is the reliability and maintenance of components and complete
systems. This is now the subject of serious discussions and a programme to tackle these issues is now being formulated jointly with the consultants.

Finally, we have been examining the implications from the land transmission viewpoint of the geographical location of wave power stations. Based on what now seems a very optimistic 50 kW/m maximum continuous rating, and the assumption that generation and demand in Scotland will remain reasonably balanced, to utilise that 12 GW would involve two 750 kV circuits to the Midlands (shown in Figure 31). The CEGB estimate of the cost from the generator to the bulk supply point (but not the platform or sea bed rectifier/transformer containers) is about £400/kW for the preferred transmission scheme. This could reduce to £300-£330/kW if generation synchronous with the grid could be achieved. The alternative (shown in Figure 32) is also 12 GW but dispersed in three groups. No 750 kV is required; two 400 kV lines from the Hebrides and uprating the existing Scottish transmission would have costs of £230/kW, but the north-east and south-west sites would cost only £145/kW and £165/kW respectively. This leads to an average of £180/kW which, on the synchronous route, could reduce to £110/kW.

I have only been able to touch on the wide range of topics in which TAG 6 has an interest — the relationships may often seem obscure. However, if I may summarise the present position, we have failed to solve the duck’s problems and we are still a little worried about rafts but the generation and transmission problem is tractable — it only requires a reasonable input and that is best obtained from air or water turbines.

The electrical route is neither inefficient nor unduly expensive and, if it were required urgently, detailed design and construction could proceed without delay. Individual devices may founder, but wave power development will not be limited by
problems of generation and transmission alone.

DISCUSSION

H B Stansfield (Kennedy & Donkin)
Considering the merits of immersed rectifiers as opposed to platform-mounted stations, both in mind that the devices nearly all require a reliable auxiliary supply for maintaining bilge pumps, air compressors and things like that. We had in mind if we had, say, small gas turbine equipment on the platforms we could feed back down the AC flexible cables in calm weather and maintain the devices in a viable condition; we couldn't do that if the rectifiers were on the sea bed with no generating plant.

I Glendenning
I think that's a fair comment. One of the lessons from the work that has been done is that all the influences favour large structures with interconnected power systems on board. Among these influences are the need to maximise device performance, to minimise mooring problems and to minimise main structure movement which relieve flexible cable problems. Interconnection (whether electrical, hydraulic or pneumatic) of a number of single generating units enables flexible cables to operate to the limit of their power capacity with an already smoothed power supply. Under these circumstances I suspect that it may be more viable to have emergency supplies actually produced on board because they would be shared between a large number of systems. This is a level of detail into which we have not moved; it's not really appropriate at the stage where no firm systems actually exist, but it is a very important message for the future.

S H Salter (Edinburgh University)
One of your slides showed up to 100 boxes on the sea bed. Each of them had a transformer and rectifier, which I know are very reliable, but they also had a seal for a cable coming and another for a cable going out and another hole for some wires coming down from above - so that's 300 seals. Now I quite believe that you can get most of them to work for a lot of the time, but I don't think you can get all of them to work all of the time. It seems to me that if water gets into any one of them you have got a short to the frame which might have 100 kv or so; that means that you lose the whole lot. I think that if we have to get the reliability figures up to above 98 or 99%, we have to understand the difference between things in series and things in parallel. If we do understand that, we might find that lots of independent things in quarantine will be more reliable. Can you tell me what you are going to do about those 300 seals?

J McConnell (Pirelli)
The problem is very much there; this is why we at Pirelli at present favour the Kennedy & Donkin scheme of putting all these things on a platform, at least initially. It means that you have a chance of making them work at the beginning. To give you some idea of the size, a 250 kv DC sealing and, even in oil, is probably about 3 m long; that's not a plug and socket, it's just a termination. To get these sizes into units that can be mated and demated underwater is a terrible problem - it is certainly something that has to be looked at.

I Glendenning
We are not pretending that it's easy, but we do have a flexible approach.

J Berry (Bertlin & Partners)
This is the first time (and I am very glad to hear it), that the words 'platform' and 'fixed structure' have been mentioned. I am a practising civil engineer and find that most electrical things go wrong because damp sets in. The things I deal with are generally on the water, on a fixed structure or immediately beside the water. I know that when it is actually on the water conditions are even worse; you will find damp inside even the most simple things like cast-iron waterproof boxes. So I think it is essential to have some fixed structure. I think you will also need the maintenance base at frequent intervals and you have to have people. The need for them has not been discussed, but I find that generally most things go wrong and you have to have people around to deal with it; a fixed platform as a base for them is essential.

Prof M J French (Lancaster University)
I just wanted to ask about the figures you showed for the Wells turbine which is very interesting. Are the efficiencies given total-to-static efficiencies?

I Glendenning
Yes.

J Gosden (Electricity Council)
I wanted to ask Mr Glendenning to enlarge upon the problems of operation in parallel with a system. I believe there is some confusion about this, even in Mr Glendenning's own remarks; for instance he commented that one insists on a high load factor. I would repeat the point that Prof Swift-Hook made yesterday, that the load factor is merely part of the overall economic assessment. As I understand it, the point about this is that you do not regard tidal power in any way as contributing to the total capacity of the system, so that when it generates it is saving other forms of generation; it is therefore just a matter of the total amount of units that can be developed over the course of a year. My second question is about the short term fluctuations: this is no new problem because if you put a fluctuating generation in parallel with a steady load it becomes rather like a fluctuating load. Things like arc furnaces are quite similar therefore; I take it that this is the basis on which the study has presently shown that up to 20% could be tolerated. Can you give us more information on this?

I Glendenning
You are absolutely right: what obviously matters is going to be the final cost of the landed energy. I doubt whether there is very much of an opportunity to get wave energy onto the system on demand - although the wave energy system may well be required to turn off on demand if the land system is unable to accept power: that's a real operational mode that will obviously have to be considered. So it is the cost of the final energy that matters. My remark was only based on the not unreasonable assumption that, whatever we do with wave power, at the end of the day it is going to be expensive. So, if your top line is a high cost per unit of installed capacity, in order to get a low energy cost it really is implicit that the system has to be designed to a power rating which permits a high load factor. It's obviously far more complex than that; it is the subject of several optimization studies at the moment, on very little information. Turning to your other question on short-term fluctuation - the major concern here is in fact in the design (for operation, control, stability and survival generally) of the local components which are subjected to the highest fluctuations. If you like an ordinary generator provides a fluctuating output - after all that is what AC is - it's at a fairly high frequency but it hasn't the same variance as the outputs from the primary converter on a wave power station. If we did get back to this ideal linear load, for example, and we really did want to take everything that came at us, we would have to design a system which at the front end at least had an enormous power handling capability just for the benefit of getting out a very modest amount of power at the other end.
after smoothing; so it's a purely practical problem.

R M Gove (SSEB)

I noticed a reference first of all to 22 kv as one of the collecting voltages. I would like to point out that 22 kv in the supply industry is rather an obsolete voltage; it would be a pity if one started off in a new technology with equipment which is not in general use. My second point concerns the security standards of the transmission schemes that Mr Glendenning described. When one adds generating plant to a transmission system there are all sorts of security standards which have to be observed to ensure continuity of supply; normally in a large installation of this type one would have at least four circuits, to allow any two to be out at any one time and still allow sufficient transmission for the generating source to deliver its energy to the consumer. I would like to be sure that the security standards of the transmission schemes which Mr Glendenning described are in accordance with the standards used for other plant in the country. I also want to make one point about the environment. Mr Glendenning mentioned that he could see no reason why construction could not proceed without delay. I would sound a note of caution there: the transmission line routes he showed come through some of the most scenic country in Europe and you can expect very severe environmental problems in getting way/leave for transmission lines over these routes.

I Glendenning

Three good points. First of all the 22 kv system: we are not actually proposing there should be any of that on land. The aim is to take maximum advantage not of an obsolete technology but of a rather advanced technology in flexible cabling; it will be completely isolated from the land-based system by the whole DC link. Second, we have discussed security standards at odd times in the Committee. Yes certainly, for main generating plant going on to the system the security standards do have to be very high indeed – that's a prime consideration. In the wave power situation it would be possible to provide redundancy within the transmission system; in view of the costs we have been talking about for some locations, that wouldn't actually be a very high cost in the scale of overall wave power economics. That goes some way towards answering the point that Stephen Salter was making originally. It is possible to contemplate quite significant redundancy in that electrical transmission link, even if we can't afford it right at the front end, but at the present time we haven't included that. It's not clear whether wave power's nature and final role on the system would necessarily justify major expense to get true security of supply, although obviously we do want a reliable system. Third, your colleagues at the North of Scotland Hydro-Electric Board were indeed of the opinion that we would stand a much better chance of getting power ashore from the east coast than from the west coast from the environmental point of view. I was referring only to the design of the equipment and the means of deploying and constructing it; it is sufficiently well understood not necessarily to go ahead with making it but at least to get down to the detailed design and then make it. The technology is identified, it just requires the word 'hold' or 'go'.

Dr T Carstens (River and Harbour Laboratory, Norway)

Perhaps with the exception of the ducks, high pressure hydraulic systems for transmitting energy from many absorbing devices to fewer generating devices have been conspicuously absent from the designs presented here. Have these been seriously studied and then discarded, or have they been left out from the outset perhaps because they are too unreliable or for some other reason?

I Glendenning

Yes, they have been considered, at both high and low pressures. We do however have a fairly strong feeling within the group, that there is an ideal range in which to operate hydraulic equipment. At the very low head end (the HRS end), the heads are too low for machines to come within a seriously economic price range. At the high pressure end, we have very large numbers of fine-tolerance components, which in the normal course of events do require a lot of attention and very careful quality control of the fluids that are being used. We wonder whether this is really compatible with unmanned operation for any extended length of time at sea. It is very much unquantified at the moment – this is another area of detail that does need attending to. At the moment we just think that if we keep the hydraulic operating pressures between say 15 and 50 m head then we are probably in the right range to take the best advantage of technology without going too high.

Dr D Mcilhagger (Queen's University, Belfast)

Reliability is vitally important on the WEC itself. I would be horrified to think of a generator, an alternator and possibly a transformer and control gear, on the Queen's University point absorber device. Our sea-going experience showed us that a generator can quite easily be dumped; it's important that if one device is immersed in this way, it should not upset the whole sub-system. Our system uses permanent magnet alternators rectified at the terminals, (rather reversing your arrangement), then connected in series through one, two or three parallel links to the next device, building up a group of say, 40 or 44 kv, and then possibly transmitting to shore by two groups of DC flexible cables. It involves a good deal less cable, and all control can be exercised on the shore or on a platform or in a sub-sea cavern; this offers good advantages compared with methods which concentrate a lot of control on the device itself where it would be very difficult to maintain and service it.

I Glendenning

I honestly don't think there is too much difference apart from detail between what you are describing and what we have been describing. I know that yesterday's presentation said that you preferred permanent magnet excitation. That's fair enough; it seems that some control is needed at sea in order to maintain our machines in the right efficient operating regime (not just the generator, but also the turbine that's driving it, in your case an air turbine) and to keep the output as level as possible. I don't see why that control should be particularly unreliable or particularly expensive. I think your first point gives the key to the difference between your position and our position. You are trying to optimize a system to a particular device, the point absorber device; while I don't want to be seen to be writing off your device, it is our impression that it would be much better to have larger devices, (the KaiMei type of vessel or the long oscillating water column), where we can provide good environmental conditions for equipment and allow a degree of sophistication which enables us to optimize the system. We are starting from the system and looking for a device; you're starting from the device and looking for a system. I hope we will meet in the middle.

A Comyns-Carr (Wavepower Ltd)

I was interested in the degree of benefit from a relatively small amount of inertia storage that IRD investigated. In the design that we presented yesterday, we were thinking of considerably more storage than the 5 seconds – something in the order of ½ minute to 1 minute. What sort of additional benefit would you think might be achieved by that degree of storage?
IRD have considered a range of time constants for the storage, up to 15, 20, 25 seconds. Over the whole range of operating conditions that they have considered, they found that there is really no point in having storage levels outside the 5 to 15 second range. They would not claim yet to have come close to optimizing where it is, (whether it should be at the lower or the upper end of the range) because there are so many conditions in which the system is required to operate efficiently. Earlier on we examined storage for hydraulic systems, however, and found that we did need rather more storage than we require in this system. The two are not quite comparable – in hydraulic systems if you could get 10 to 15 minutes you would be happy; it's a different type of problem.

Sir Christopher Cockerell (Wavepower Ltd)
In Scotland there are quite a number of hydro-electric storage systems. Presumably they are put there because they are useful to the electricity board. Has real consideration been given to pumping seawater up a hill?

I Glendenning
It would be unfair to say that lengthy consideration had been given to that. Pumped storage is put in for very specific reasons, which by and large are not present in the wave power situation. The costs of pumped storage are such that they would not bring any economic advantage to wave power in terms of the way in which they might enable us to operate the system differently. That was taken into account by our planning department's study which said we could have 20% of variable resources on the system before we actually have to worry about putting storage in.
I should like to outline briefly some of the problems involved in the area of fluid loading and structural design of wave energy devices, with particular reference to the work of Technical Advisory Group 3 (TAG 3), which I have chaired for the last 2½ years. TAG 3 was set up in 1976 with the aims of:

- providing specialist advice to the Steering Committee and to device teams in the areas of fluid loading, materials and structural design;
- initiating a programme of generic research which would include provision for the long-term needs of device development.

Initially TAG 3 was also responsible for mooring but as the importance and complexity of anchoring and mooring problems became apparent a separate advisory group (TAG 4) was set up to deal with this problem area. The present composition of TAG 3 is indicated in Figure 1.

Safe and efficient design of a wave energy device will require:

- accurate prediction of wave-induced motions and loads, including mooring forces, with reference both to extreme loads and to histograms of cyclic load which will tend to cause fatigue damage;
- evaluation of structural response, i.e., deformation and stresses under prescribed loads;
- synthesis of detailed structural design with provision of reliability and minimisation of whole-life cost as the main design objectives.

Evaluation of design loads may be based either on theoretical analysis or on experimental data or more probably on a judicious combination of these two. Linear analysis methods are now well-established for ships and floating offshore structures. These methods involve setting up and solving multi-degree-of-freedom equations of motion (summarised in Figure 2) for a floating structure in which the mass, damping and stiffness coefficients must include contributions from the structure, the water, the power take-off system and the mooring system. The solution process involves the following stages:

- evaluation of mass, damping and stiffness coefficients, in which hydrodynamic components are estimated either by approximate methods (such as use of Morrison's equation or known results for simple forms) or by strip theory or diffraction theory
- for regular long-crested waves assumed to be sinusoidal in form the exciting forces are also sinusoidal and the equations of motion can be solved directly to obtain response amplitude functions for a complete range of wave frequency and direction
- a directionally distributed wave spectrum defining an irregular wave condition can then be converted into a response spectrum, from which short-term statistics of motions and loads in a particular sea condition can easily be derived
- finally by referring to the long-term statistics of parameters defining wave spectra (i.e., significant height, mean period and directional spread) short-term distributions can be combined to provide long-term, whole life probabilities of non-exceedance for motions and loads together with the histograms of cyclic loading

### EQUATIONS OF MOTION FOR FLOATING BODY

\[ M\ddot{\theta} + C\dot{\theta} + K\theta = F(t) \]  \[ \text{[1]} \]

**Linear Analysis Process:**

(i) Evaluate \( M, C, K, F \): hydrodynamic coefficients from approximate analysis (e.g., Morison's equation), strip theory, diffraction theory or experimental data.

(ii) Solve equation \([1]\) for regular long-crested waves (sinusoidal excitation) to obtain motion and load response amplitudes (RAO).

(iii) Wave spectrum \( X \times (\text{RAO})^2 = \text{response spectrum}.\)

(iv) Derive short-term probability distributions from properties of response spectrum.

(v) Combine short-term distributions to obtain long-term (whole-life) probabilities of non-exceedance and histograms of cyclic (fatigue) load.
which are required for evaluation of fatigue strength.

Considerable progress has been made in the last two years in the extension and adaptation of existing analysis methods to deal with wave energy devices. Important contributions have been made by Dr Hogben and Dr Standing of NMI and by Dr Ward and his colleagues at BSRA: significant contributions have also been made by Mr Count of CEGB and by several of the device teams. We have illustrations of the accuracy which can be achieved by this analysis. Figure 3 compares the results of the BSRA analysis and the NEL tests of the OWC device showing power take-off efficiency over a range of wave frequency. Figure 4 shows a comparison between Salter's two-dimensional experiments, NMI's approximately two-dimensional calculations ('ducks moving together') and calculations on three ducks mounted separately on a fixed spine.

There have been some differences of opinion about the usefulness of these analysis methods and objections have been made by some device team members to their development at the present stage in the programme on grounds of their complexity, the cost and effort involved in their use and because of the obvious non-linearity of device response in extreme wave conditions. The observation that can be made on this point is that similar objections were made 15 or 20 years ago with reference to ships and offshore structures but that linear response analysis has now become a standard part of the design process for ships and offshore structures.

While linear analysis obviously cannot be expected to deal accurately with extreme device behaviour, it is clear from comparisons of analysis with experiment that good accuracy can be provided under moderate wave conditions. It seems likely that linear analysis will prove useful:

- for evaluation of device response in moderate waves, particularly in relation to efficiency of power take-off
- for evaluation of fatigue loading, where most of the damage is likely to be caused by small and moderate waves
- as a starting point and possible basis for semi-empirical analysis in assessing extreme motions and loads.

In order to investigate extreme motions and loads a theoretical attack must be made on the non-linear response problem. This involves solving equations of motion with displacement-dependent coefficients, either by number-crunching numerical integration on a digital computer or by representing the problem on an analogue or hybrid computer. A start in this direction has been made by Dr Bellamy's colleagues at Lanchester and under TAG 3 auspices a study has been undertaken by Dr White of Cambridge University into the application of hybrid computing to wave energy devices.

The behaviour of a floating device under extreme wave conditions is likely to be affected by impulsive loads caused by breaking waves and slamming. Breaking waves have been convincingly demonstrated in the tank at Edinburgh as shown yesterday in Stephen Salter's presentation. The effects of breaking waves on Cockerell rafts have been investigated by WPL, and I understand that on the basis of small-scale observations, by simple adjustment of the nose geometry in the leading raft, it was possible to achieve a marked improvement in response to breaking waves. Some interesting theoretical contributions on the form of breaking waves and their impact on structures have been made by Prof Longuet-Higgins but it seems clear that our understanding of breaking-wave effects is far from complete and that these effects, which vary radically with device geometry, should be investigated carefully as part of any continuing wave energy programme. The problem of slamming, caused by emergence of part of the structure followed by impact on re-entry into the water, is also potentially important as illustrated in Figures 5, 6 and 7.

The problem of local slamming damage can probably be overcome, in wave energy devices as in ships, by robust design of areas exposed to impact. A more serious problem is the possibility that severe vibratory bending of a long slender structure could be excited by slamming forces. In slender ship hulls it has been found that slam-induced bending moments may be of the same order as, and may be superimposed upon, maximum wave-encounter bending moments.

Having dwelt at some length on the theoretical approach to evaluating device behaviour, I must say that I believe, I think along with the device teams, that the main thrust of the wave energy programme should be experimental. On the question of the relative merits of large and small-scale testing, my view and that of TAG 3 is that trials at Intermediate scale (say 1/10th scale trials such as those in Loch Ness and the Solent) are absolutely essential as a stepping stone between small-scale tests in the laboratory and tests on a full-scale prototype, providing experience of "going to sea", helping to resolve uncertainties about scale effects and possibly providing field information about corrosion and fouling. However such trials are extremely expensive and are fraught by lack of control over wave and weather conditions. For these reasons, and in view of the excellent controlled wave conditions, including extreme and breaking waves, which can now be provided in tanks such as that at Edinburgh, it seems
example, where structural deformations are inherently coupled with overall motions: in such cases it is necessary to represent structural stiffness and degrees of freedom corresponding to structural deformation in the equations of motion (or to represent structural stiffness correctly in model tests). In other cases, where a device consists of a single rigid body or a system of connected rigid bodies, structural response can be estimated separately from overall motions.

- The elementary "cube-square" law should be borne actively in mind when designing model tests, that is the fact that while forces increase as the cube of linear dimension, areas resisting forces increase as the square, so that stresses increase in proportion to linear dimension: consequently it is impossible, even in perfectly scaled models operating in perfectly scaled waves, to obtain a direct assessment of structural capacity. Small-scale models will tend to give a grossly optimistic indication of strength.

- Although for most practical purposes and certainly for initial design purposes stresses and deformations can be estimated satisfactorily using simple formulae and data curves, it is likely, for wave energy devices as for ships and offshore structures, that use of sophisticated finite element methods embodied in computer programs such as NASTRAN, SESAM and ASAS will become necessary as part of the final design evaluation. A study of the application of FE analysis to wave energy devices, together with the interfacing of NASTRAN with the NMI and BSRA wave response programs, has therefore been undertaken by Lloyd's Register so that if and when the need arises for such analysis we will not be caught with our pants down.

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<tr>
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On the subject of evaluating structural response, i.e., deformations and stresses in a structure, I would like to mention three points:

- It is important to identify 'flexible' systems, of which a string of ducks on a long flexible spine is a good
Dr Hudson shortly describes investigations being carried out by SMBA and the AERE Materials Development Division into the important problems of corrosion, corrosion-fatigue and marine fouling. British Shipbuilders have completed a useful study of the design and cost of wave energy devices constructed in steel; this work was undertaken to correct an apparent bias in favour of concrete in the earliest reference designs: steel construction now appears to be fairly represented in the latest RPT reference designs. Lloyd's Register have been commissioned to prepare, in consultation with device teams, preliminary Design Guidance notes for wave energy structures. In the short-term it is hoped that this document, which aims to adapt for wave energy devices the relevant parts of existing codes for steel and concrete ships and offshore structures, will be of immediate use to design teams; in the longer term it is possible that informal guidance notes, drafted with the concurrence of device designers, will serve as a basis for mandatory rules which, as in the case of offshore structures, are likely to be imposed by Government if and when wave energy devices take to the sea in large numbers.
MOORING AND ANCHORING OF WAVE POWER DEVICES
R Hancock (National Engineering Laboratory)

1. The life and safety of a device depends upon its mooring.
2. Present mooring techniques are inadequate for wave power.
3. Cost is all-important.
4. Theoretical predictions will be useful but for survival simulations tank model tests are vital.
5. It is one thing to moor a device for months — but another to moor it for years with minimum maintenance

Figure 1

There are five main points (listed in Figure 1) that I wish to get over, which I hope will enable you to sense how we see mooring fitting into the overall wave power theme, and to hear what is being done to overcome the problems we foresee. It is no exaggeration to say that upon the mooring and anchoring system depend the life and safety of the device and anyone who may be near or on it. Figure 2, a photograph of a tanker in a gale, reminds us that the sea is probably the most unpredictable and severe of the elements with which we have to contend in the present-day life. In spite of the modern technology that can take a man to the moon, ships still sink, moorings break loose, people are lost overboard, and frightening things happen (as in Figure 3) when tons of water hit the deck of a ship.

This is the element in which we are proposing to place very large and complex machines upon which a significant proportion of our power in the future could depend. It behoves us to consider very carefully the problems of keeping these devices safely in place. It will not have escaped your notice that several people proposing wave power devices have chosen to avoid the use of moorings altogether, either by going beneath the waves or by siting the device on the seabed.

This brings me to my second point. Ships have been anchored and moored ever since we had ships. More recently, unlikely-looking devices (such as the one shown in Figure 4) have been anchored in very rough conditions in the North Sea, and experience is being built up; but it must be remembered that no ship’s captain in his right mind would try to anchor his ship in the middle of the North Atlantic. Nor would a tanker’s captain expect to stay connected to an SPM on an exposed oil field mooring in the worst conditions (see Figure 5). While present experience allows for mooring and anchoring of vessels in exposed severe conditions, it will also expect these vessels to be able to leave their moorings and survive in the traditional way by making for open water when conditions get very bad.

It is significant that in the North Sea at the moment no moored rig is expected to withstand the most severe storms that could arise. Pipelaying and crane barges are the largest structures being moored or anchored at the moment. Figure 6 shows a pipe-laying barge with its accompanying mooring system which, as well as holding the barge against the weather, also provides tension on the pipe. The important thing to notice here is that, although this is a wave-power-sized structure using large anchors, it has a temporary mooring and is always accompanied by a number of anchor-handling vessels: in extremes these vessels can use their power to hold the barge in position or to ride out a storm.

It is very unlikely that a wave power system on the scale presently being visualised could be designed with such an option in mind. This brings me to point three — that the cost of the mooring system is all-important. Present predictions suggest that mooring costs range from 4% to nearly 30% of total capital costs of a wave power station. Maintenance costs have still to be added. I personally believe that we shall find that the lower of these figures is optimistic. Wave power cannot afford moorings at any cost; cheaper solutions must be found, and mooring forces must be minimised.

An object moored or held rigidly in a wave system must withstand the full force of the waves. If, however, the object is
How do we predict what forces have to be designed for – the fourth point on the list? Mathematical modelling and analytical tools will play an important part in the design of moorings, but they have some real limitations. Present techniques for predicting drift force and response in regular waves are probably adequate in moderate seas, but are not so satisfactory in random seas. A particular problem is slow drift oscillation effects caused, for example, by:

- change in momentum of surface waves as they are scattered and radiated by structure
- out-of-phase motion of structure, by changing orientation
- very long waves of low amplitude
- ‘set down’ due to high and low wave groups having slight change in mean water level between them.

A further problem is that ‘survival’ condition seas give rise to non-linear conditions with steepness ratios greater than 1/20, and the breaking waves that have already been referred to. But survival conditions are perhaps the most important design situation, and it is felt that the most useful prediction method under these conditions will continue to be model testing. Positive action is being taken to provide the device teams with the most up-to-date advice on mooring model test techniques, particularly relating to simulation of slow drift oscillation effects. Mathematical modelling will be important for assessing fatigue requirements on mooring components and for interaction with programs modelling the normal operating performance of the converters, and a state-of-the-art study is being commissioned to indicate to the wave power teams the design techniques and tools presently allowed to move to a greater or lesser extent with the waves, the forces involved will be less. This is the philosophy that has so far been adopted in the thinking on several wave power device moorings. Another is to use the long backbone approach, when it is expected that wave forces will tend to cancel out over its length.

There are limits to the use of compliance, as indicated in Figure 7. If the mooring is too compliant or the devices very close to maximise collection efficiency there is a danger of touching. Further there is the problem of crossing mooring lines. The problem of optimising compliance, cable strength and spacing for a given device is at the centre of the mooring design problem.
available and to identify where further work is most needed, and can be usefully applied.

My last point is related to the first. It is one thing to moor a structure in an exposed sea situation for a few weeks, or even for a few months, but to keep it there year in, year out, without excessive cost in maintenance or very excessive overdesign by today's standards is a considerable problem. Figure 8 shows a dramatically worn shackle, which is representative of the problem of trying to use existing marine components of the types shown in Figure 9 for long-term duty where maintenance and replacement is not possible. The solution, I believe, is that these simple components will be replaced by more sophisticated (and expensive) parts designed and tested for maintenance-free life. We are already seeing this, of course, in components like the swivel on an SPM.
The connection between a vessel and an anchor is usually by chains which provide compliance. They are strong and heavy, and store compactly, but their life can be variable. Steel wire cables are being increasingly used and in the near future man-made fibre ropes may well come into their own. Little is known, though, of the performance of these under very long extended life conditions. Without accelerated testing the load/life curve shown in Figure 10 illustrates the problem. Work has already started within the wave power programme to provide more basic information on man-made fibres and corrosion fatigue in wire ropes must be looked at; use of rubber (elastic bands if you like) is also being investigated.

Now what about anchors? Many drag anchor types exist and may be satisfactory for long-term use. The holding capacity required in one prediction is greater than is available as a single anchor unit (see Figure 11) but manufacturers believe there is no barrier to size; whether the holding power scales in proportion remains to be seen, and in any case that is difficult to test. The vast number of anchors required in the grand wave power scenario would require dedicated laying and maintenance vessels and it may well be that one of the new self-burying embedment anchors would be more economic if developed in a size adequate for the task.

So far in this world of high technology man has still found no certain way to overcome and survive the worst excesses of the surface of the sea. This is a measure of the problem before us. To ensure long-term integrity extensive land-based component testing under simulated load conditions is required. Accurate surveying of the sea-floor will be necessary to ensure choice of anchors and I believe that the first large scale devices to go to sea will have over-designed and hence expensive moorings requiring considerable maintenance. Experience and development should show where improvements can be made.
MATERIALS ASPECTS OF WAVE ENERGY CONVERTERS
Dr J A Hudson (Materials Development Division, AERE Harwell)

An assessment is being made by myself and colleagues (Dr D C Phillips and Mr N J M Wilkins) of likely materials problems facing WEC development. This paper will summarise generic problems identified to date and differentiate areas of known and unknown technology, although specific problems arising as the various device designs develop are also being considered. It is important to emphasise at the outset that the technological gaps will not, in some cases, be filled quickly so that the sooner experimental work can be started the better.

Previous papers at the conference have described the current designs of Wave Energy Converters (WECs) and their principal components. In Table 1 the materials which will find application in these components and the phenomena likely to influence their durability are listed. Not all the areas have yet been fully reviewed and so this paper will concentrate on corrosion and fouling aspects.

Table 1
Materials and Possible Problem Areas for Wave Energy Converters

<table>
<thead>
<tr>
<th>Materials</th>
<th>Phenomena</th>
</tr>
</thead>
<tbody>
<tr>
<td>Structural Steel</td>
<td>Marine Corrosion</td>
</tr>
<tr>
<td>Reinforced Concrete</td>
<td>Stray Current Corrosion</td>
</tr>
<tr>
<td>Pre-stressed Concrete</td>
<td>Corrosion Fatigue</td>
</tr>
<tr>
<td>Alloy Steels</td>
<td>Wear and Fretting Fatigue</td>
</tr>
<tr>
<td>Reinforced Plastics</td>
<td>Creep Rupture (Plastics)</td>
</tr>
<tr>
<td>Rubbers</td>
<td>Marine Fouling</td>
</tr>
<tr>
<td>Cu and Ni Based Alloys</td>
<td>Impact Loading</td>
</tr>
<tr>
<td>Ti and Alloys</td>
<td></td>
</tr>
<tr>
<td>Stainless Steels</td>
<td></td>
</tr>
<tr>
<td>Anticorrosive and Antifouling Coatings</td>
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</tbody>
</table>

The corrosion of metals in marine environments is a large area of known technology. With correct application of this technology straightforward corrosion problems could be obviated. For example, the low-pressure seawater-hydraulic system envisaged for the Cockerell raft device could be protected by a cathodic protection system similar to ones already successfully employed in power station cooling water systems. Although the means exist to combat corrosion there are many instances where they are not correctly employed. An example of this is shown in Figure 1, a photograph of a 304 stainless steel bolt in a 316 stainless steel plate. The bolt has virtually disappeared by crevice corrosion after only three months' exposure to seawater. Thus although steel structures could in theory be protected against corrosion for, say, ten years by correct application of modern coatings, current shipbuilding practice would suggest that this is unlikely. In this context, reinforced concrete seems to offer the better prospects for long-term durability of the main WEC hulls.

A potential problem for WECs is stray current corrosion from the self-generated electricity in the generation and transmission equipment. There are many examples of corrosion by stray DC and the phenomena is reasonably understood. However some uncertainty exists in the literature on possible AC effects. Experiments are under way at Harwell to investigate AC stray current effects on both unprotected and steel reinforcing bars in concrete. So far no rectification of AC by passive films has been detected. However some breakdown of certain protective films and enhancement of conventional corrosion has been observed and further tests are planned to investigate these effects further. Many components of WECs, the mooring system of floating devices in particular, will be subjected to fatigue loading. The understanding of corrosion fatigue behaviour is far from complete although there is now considerable effort devoted to the investigation of structural steel[1]. An example of the effect of seawater corrosion on the fatigue endurance of a steel wire is shown in Figure 2, which also illustrates how cathodic protection can restore the dry fatigue lifetime of the specimen[2]. The tests represented in Figure 2 were carried out at 100 Hz, a high frequency in terms of WECs. It is now believed that corrosion is enhancing fatigue crack initiation at these frequencies and that at frequencies below about 1 Hz an effect of corrosion on crack growth rates can occur. Experiments done as part of the United Kingdom Offshore Steels Research Project[1] have shown that crack growth rates some six times the 'dry' rates can occur in structural steel tested in seawater at 0.1 Hz, a frequency typical of wave
The tests are designed to investigate effects of corrosion, and the final design of any WEC mooring system will have to take these effects into account. Work under way will generate fatigue endurance curves for the existing NEL programme have since been suggested. The fibre rope, work has also begun in this area and additions to fibre and metal ropes are further areas of relatively unknown technology. The fatigue and corrosion fatigue behaviour of man-made WECs.

It is desirable to know the likely fatigue conditions to be met in practice. To this end, tests of cable arrangements in wave tanks should be compared with fatigue endurance curves for small ropes which had received different amounts of prior exposure to seawater. A substantial testing programme is being proposed by NEL and Harwell to investigate the failure of metal ropes in seawater. The tests are designed to investigate effects of corrosion, loading frequency and cathodic protection. Because of the poor knowledge of the fatigue behaviour of wet man-made fibre rope, work has also begun in this area and additions to the existing NEL programme have since been suggested. The work under way will generate fatigue endurance curves for three types of existing rope up to about $10^6$ cycles at 0.1 Hz. Future experiments will investigate the possibility of accelerated tests, the effects of rope length and choice of end fittings and the fundamental mechanisms of the fatigue failure.

The final design of any WEC mooring system will have to take into account the disposition of flexible AC power cables. The bending fatigue behaviour of these cables and their steel armouring must be determined and preliminary work has been initiated by Pirelli. In the design of future tests it would be desirable to know the likely fatigue conditions to be met in practice. To this end, tests of cable arrangements in association with future model tests in wave tanks should be considered.

Marine fouling and its effects on the durability of offshore structures are receiving increased attention. This is not only as a consequence of effects such as blockages and weight and size increases, but also because of possible interactions with corrosion and corrosion fatigue. Data collected from the United States and a few UK sites suggest that the annual build-up of hard fouling (barnacles and mussels) on full scale WECs could be in the region of 1-2 tonnes per m of wave front for current device designs. In order to investigate the actual incidence of marine fouling in areas of suitable WEC deployment, experiments are being carried out by the Scottish Marine Biological Association in a region ten miles west of South Uist. Test panels have been exposed for one settlement and growth season and most of the anticipated hard and soft fouling organisms have been observed. Further tests are planned for next year which will incorporate simple corrosion and cathodic protection tests. At the moment there is no accepted description of the interaction of fouling and cathodic protection systems and a need exists for further well documented tests.

There is a wide range of antifouling treatments and different ones will find applications in different areas of WEC design. No coating in current use has a lifetime of more than four years although some experimental paints have shown at least nine year antifouling lifetimes on steel test panels. Coatings on concrete have not been fully investigated although preliminary work has been done by Sea Energy Associates. In this work, a series of concrete test panels with different coatings has been exposed to seawater at the Isle of Luing and a further series has been exposed off the Isle of Shona. So far the least fouling has been found on a plaque coated with black polyurethane. If concrete is to have widespread application for the main structures of WECs further work on antifouling and anticorrosion coatings will be necessary.

Finally, I should like to mention the role of rubbers in future WEC development. Existing designs incorporate rubber in seals, valves and flap gates and consideration is being given to its incorporation into compliant mooring systems. In addition, the most promising new WEC from a structural cost point of view appears to be the Lancaster University device which employs large flexible air-filled bags. Thus there are several applications where the durability of rubber-based components in seawater is essential. Although there is reason to expect good fatigue behaviour from wet rubbers, the evidence is sparse and work will be needed in this area.

References

DISCUSSION

Dr P K Probert (Nature Conservancy Council)
As a non-engineer myself I thought an advantage of floating devices would be that at least they could be brought into sheltered water for overhaul, but looking at the massive mooring gear required I assume now that once the device is deployed that would be permanent for its life span. Is that correct?

R Hancock
I believe this will be the case. They are massive components – they are either massive or there are very large numbers of them so one can’t really envisage slipping moorings in very bad conditions. There have been suggestions that when the storm gets bad we sink the device to the sea bed; these sort of things may happen. I think we should also be paying attention to wave-farming, as Stephen Salter put it, but as you have seen from Ian Glendenning’s talk, this also has a very long way to go.

I A Knights (CJB Ltd)
In the offshore oil industry now there are two existing permanent moorings, one in the South Atlantic, another one in the Mediterranean. There is one under design at the present moment for the North Sea which I believe is for the Fulmar field, and a further one is proposed for the Beatrice Field, north of Scotland. I would also like to get the speakers’ views on yesterday’s presentation by RPT. In RPT’s financial analysis a figure of 3% was quoted as the annual cost for maintenance and repair of structures. In the light of the talks this morning on corrosion and on mooring problems do the speakers feel this is a reasonable percentage to use?

R Hancock
I am pleased to hear about these permanent moorings. I take it that you will be prepared to let us come and put instruments on them to make measurements and monitor the process; if this were possible I think it would be very valuable. We have discussed on TAG 4 the possibility of doing at least a design study on a moored object in the North Atlantic on site, to get information on such things as life, maintenance cost, etc. I think that would be part of the answer to the next part of your question.

P J Clark (Rendel Palmer & Tritton)
First of all that figure of 3%, if taken for specific items is far too low. It is very much a figure to be taken globally. For a very large concrete structure, (and a lot of money is in the concrete structure), that structure lives and sooner or later it dies; there is not very much you can do about it by maintaining it. The 3% corresponds to a much larger percentage on those items which will need maintenance. The second point is that the figure already presupposes an improvement in the life of things such as moorings, beyond those which we have at present. If wave power had to live with mooring components which are now used in the offshore industry, there is no way it could be economical. So it is already pre-supposing new materials in mooring which are not at present in use.

R Freer (SCOPA)
First of all I think that Dr Smith would anticipate needs to be solved in a 1/10th scale tank, I would have thought that if the problem is size-dependent, the sensible thing would either to be solved at full scale or extrapolate from a smaller model. My second question is to Dr Hudson: if GRP turned out to be suitable for any structural part of a wave power device, has he anticipated the problems of fatigue which now seem to be fairly unknown?

Dr C S Smith
I think that a lot of the uncertainty about scaling relates to power take-off systems and the difficulty of scaling down realistic power take-off systems to very small, say 1/100th scale. That is not really within the province of my discussion this morning. The other types of uncertainties relate to the behaviour of structures under impact, breaking waves or slamming forces, where the phenomenon is undoubtedly influenced by effects such as air entrainment; the question is whether what is being impacted by the structure is really solid water or more like froth, and there must be doubt about whether the full-scale impact situation is realistically represented at 1/100th scale. The impact problem is also obviously affected by the structural response, and structural characteristics of a full-scale device are very unlikely to be represented at very small scale. I think that generally in impact problems the reliability of the results obtained is going to improve as scale is increased.

Dr J A Hudson
We have in fact looked at GRP. I must say that until fairly recently it’s been unlikely to be used in any large quantities in the main structures. It would have a particular advantage for antifouling of course as there are opportunities to incorporate antifouling compounds into the GRP. Until the specific components are really identified, I think we wouldn’t initiate a programme on GRP fatigue. We have received slightly conflicting advice on how serious that problem is: Dr Smith might like to comment on it, as he’s something of an expert on GRP.

Dr C S Smith
A study of the use of GRP in components of wave energy devices has been initiated by TAG 3, and will shortly be carried out by RPT with some collaboration from my own Establishment. Generally speaking GRP has the characteristic of high specific strength and low stiffness, and where stiffness is not a requirement it can be a very effective structural material. It also retains its strength and stiffness characteristics for long periods when exposed to sea water, although there is some very recent evidence that, if exposure to sea water is coupled with high stressing, very serious degradation of strength can occur. The main reasons for not using GRP are that it has very low stiffness and that it is very much more expensive than steel; if it is used it would be very selectively.

R M Gove (SSEB)
I would like to ask about the ability of these devices to stand up to a full load rejection. In rotating generating plant precautions are taken against the loss of full load, due for example to a cable fault or a short circuit of the terminals. We seem to have a different order of complexity on wave power devices in that the primary source is irregular and cannot be so controlled. If a device’s electrical output ceased for some reason while the mechanical input continued, it would overspeed; in the case of the duck I think it somersaults and later returns. If this happens and the device is then subjected to further full load waves, how does it stand up to it? What sort of calculations can be made to establish the design parameters in this case?

Dr C S Smith
There will have to be two answers to that question. It is more appropriate for Ian Glendenning to answer on the safeguards within the power take-off system. Dealing with the response of the device when the damping associated with power take-off disappears, the device teams are very well aware of this.
situation and the need to deal with it: it is being examined both in experiments and in analysis.

**I Glendenning (CEGB)**

I think you will find the situation with wave power easier than with a power station. In the power station it's not that if you lose your cable you are able to shut off steam supplies to the turbine – you have jolly well got to, and extremely quickly because that power is coming through steadily. In the wave power situation, it's not like that – any of these devices has to be able to be completely off-loaded. We saw yesterday some pictures Jim Platts showed of three rafts at 1/10th scale undamped, moving with larger excursions than loaded rafts, but not supplying any power at all into the system. The undamped model moves more but it is not a hazard to itself or anything else, (or at least it should be designed so as not to be).

**R C H Russell (HRS)**

I thought that Charles Smith was too pessimistic about the chances of reproducing elastic reflections, (one might call it structural response under wave loads) because this is done routinely in hydraulic laboratories. One reduces the Young's modulus in the linear scale and because all the stresses are reduced in the linear scale one gets strains which, being non-dimensional, are to scale. There are problems of course: the density of the material chosen (and it generally turns out to be a plastic) is too light and one has to add something like lead to get the right density; sometimes the load deflection curve is different from that of steel or concrete – but you get somewhere. I do appreciate that this does not answer the problem of foam, but apart from that do you not think that you can get structural response in fairly small models by this method?

**Dr C S Smith**

There are two issues. One is whether you can represent the gross forces, the stress resultants, effectively in your model; that issue might be affected by air entrapment inclusion in the water. I don’t know what the answer is; it may be that when we learn more about extreme wave conditions from Stephen Salter’s tank or the HRS tank we will have a better idea of whether under impact conditions the nature of the impact can be scaled effectively. The other issue I referred to earlier is whether you can scale the structural capacity effectively. I agree that perhaps by modifying the material, getting a material with a different Young’s modulus, one could model the elastic behaviour at very small scale, but one would still not be able to model the structural failure; that depends on the stress/strain curve, the yielding and buckling characteristics of the structure. One would never really achieve with a very small scale model a direct evaluation of the strength of the structure.

**J Gosden (Electricity Council)**

I would like to have more information on this question of alternating current corrosion. I am surprised that it is regarded as a very serious matter; it is easy enough to show that alternating current can cause corrosion, but only by making sure that there is enough current and voltage to produce something. In the case of this equipment I would have supposed that in the normal state all the alternating currents are fully insulated and that no operation for a prolonged period with insulation defects would occur. This leaves induced phenomena and I would like to ask therefore whether some estimate of the probable current densities and/or voltages has been made. Without such an estimate you can’t settle the level at which you would be carrying out tests.

**Dr J A Hudson**

I didn’t mean to imply that it was a serious problem at all, just that it was an unknown problem, as far as we could make out by talking to various people who might have experienced it. The problem was further complicated in our minds by some confusing interpretations of particular experiments we saw in the literature. This effect of AC on the deterioration of certain paint coatings and the enhanced corrosion of steel in reinforced concrete in the presence of induced AC are quite important: we know of work going on in one of the universities to look at the breakdown effects of AC on paint films. When we started those experiments it wasn’t really possible to do the sort of calculations you’re asking for in terms of the particular devices.

**J Berry (Bertlin & Partners)**

I would like to describe the hardware available in moorings at the moment, but I am not offering a solution to the mooring of wave energy converters. Mooring chains range from this (a $\frac{1}{2}$-inch mooring chain, with metal 19 mm diameter) to this medium size (a 3-inch chain, with metal 75 mm diameter) up to a biggest size about twice as large. Wave energy converters would not all necessarily use the biggest size of chain. For data on failures the only precedent we have to go on is ship anchor chain failures, at about 1½%; data buoy failures are about 5%, but they also have fishing and other problems.

**PERMANENT MOORING**

*Figure 1*

Figure 1 shows a permanent mooring. The catenary is always moving, and there is a lot of wear where it meets the bottom. It is usual to inspect the catenary annually. It is also usual to lift all the chains at five-year intervals for examination. It is very convenient to replace then anything that looks a bit worn; I would suggest that there would be a permanent renewal problem.

**TROT**

*Figure 2*

An alternative to the single mooring is the multiple mooring or
trot, which is shown in Figure 2.

There are many types of anchors, and there shouldn't be any problem with anchors. Figure 3 shows various types of drag anchors; there are some very funny shapes, even including concrete anchors.

All those anchors rely on a horizontal force on the anchor itself; the graph in Figure 4 shows how the anchor's resistance falls off dramatically as the cable angle increases from zero.

The development of the uplift anchor is very interesting; various types are shown in Figure 7, including the hydropin which has already been mentioned. There are different ways of holding down this uplift. In my left hand I have a link of chain. It is very heavy; chain is traditionally made in 15-fathom lengths or shots, and one shot of this chain weighs 3 tonnes. In my right hand I have a piece of Parafil capable of the same breaking load; 15 fathoms of Parafil weighs only 200 kg. So a tethered-body installation could lead to economies, but it would not have a compliant mooring; there is a great deal of work still to be done.
Dr F J P Clarke (Chairman)
Could I ask about the tethered mooring? I have been told that it can get into resonance conditions in which the forces are magnified by perhaps a factor of 10 compared with static loads: could you comment on that?

J Berry
All I can say is that I agree there are problems. It has not been used much. There is the Brent Spar Buoy which uses this principle, but there is still some catenary there, some energy absorption in the system, and it is not a directly tethered buoy of the sort in my Figure 5.
WAVE DATA MEASUREMENT AND ANALYSIS
R C H Russell (Hydraulics Research Station)

Technical Advisory Group 2 is concerned with data acquisition. It discusses the various ways in which the necessary wave data can be obtained, which features of the wave motion are worth studying, the locations that are worth studying, and advises WESC on the work to be done. The membership consists partly of oceanographers who have the necessary skills themselves to carry out some of the work and partly of device team representatives and consultants who require the data for their predictions. The requirements of the various device teams commonly differ, if only in the sites that are preferred.

There are a number of objectives: to assess the total resource available if engineering problems were soluble and costs unimportant, to assess the average intensity along favoured lengths of the coast-line -- generally off the Outer Hebrides and to the west of Cornwall where the intensity is high -- and to determine how consistent the energy source is. A further objective is to define the worst conditions at each site against which devices must be designed. One is concerned with both internal stresses in the devices and external mooring forces; and must be able to design both for rare events like breaking waves and frequently repeating loads for their effect on fatigue.

Information on wave climate can be obtained by three means:
- It can be obtained from past measurements
- It can be predicted by computations from past wind records, a process known as hindcasting, or
- It can be measured by installing dedicated instruments.

Large-scale comparisons of wave conditions in different sea areas of the world can be made by referring to publications of visual observations of waves, as in 'Ocean Wave Statistics', Hogben and Lumb, which deals mainly with shipping routes. MIAS, The Marine Information and Advisory Service, run by IOS Wormley, at the behest of PIANC's International Wave Commission, is a clearing house for wave information worldwide: it advises engineers of sources of wave data and will provide names and addresses.

It is said that UK waters are better documented as regards their waves than any other area: certainly there is a wealth of measurements obtained for purposes other than wave energy. However the sites tend to be located too close inshore as when they are obtained for harbour developments or too far offshore in the North Sea when required for oil and gas developments. Moreover some measure of wave direction is necessary for even the crudest assessment of available wave power and this is rather rarely available in existing data.

There are numerous hindcasting procedures for computing waves from the winds that have blown, of various degrees of sophistication and accuracy. Perhaps the most physically satisfactory is NORSWAM, a deep-water five parameter model making much use of JONSWAP data on the growth of wind waves, which has been operated to determine the storm wave climate in the North Atlantic and northern North Sea.

But of greatest use to TAG 2's work has been the Meteorological Office continental shelf wave-model that is run routinely twice daily. Such a model has the supreme advantage that it shows spatial gradients of wave intensity and, if calibrated and checked by observations, can provide data covering a wide area.

The determination of firm power, the unlikelihood of there being simultaneously no waves at any of the places where wave power devices are installed, will be greatly helped by there being such a hindcasting model. The firmness of power, usually shown as a percentage exceedance diagram defining for what percentage of the time the power intensity exceeds a given figure, looks like Figure 1. Spreading the wave power devices over considerable lengths of coastline that are meteorologically different makes zero or low powers increasingly unlikely; the curve of average intensity over the whole system is thereby raised.

The main thrust of the work so far has been on measurement: on the deployment of Waveriders and the analysis of their data so as to provide directional spectra at South Uist. So far we have installed two Waveriders at South Uist, one in deep and one in shallow water and another from time to time at Scillies; and we are in process of installing them at Kinnairds Head, Holy Island and Cape Wrath.

It became evident early on in the programme that the proportion of the energy flux that any device can capture depends on -- among other device-specific matters -- the direction of the wave in relation to the alignment of the device and on the directional width of the spectrum. Both these features introduce reductions in the power that can be captured. Directional spectra were necessary.

The elegant method by which IOS have synthesized directional spectra from one-dimensional spectra and meteorological information on the Atlantic will be described by Dr Crabb. Dr Mollison will describe some other analyses that have been done mostly on existing one-dimensional data.

TAG 2 has a number of other plans not yet implemented: to commission a directional buoy that will give mean direction and spread, probably at South Uist, and to install a third Waverider much further offshore than the other two in the
expectation of learning more about wave energy dissipation as waves travel into shallow water. It plans also to obtain a Waverider for the Clyde so as to assess its suitability as a site for 1/10th scale model work. It follows with interest Prof Longuet-Higgins' research work on the hydrodynamics of breaking waves in deep water and the means of measuring their incidence with a capacitance wire gauge.

Let me introduce John Crabb and Denis Mollison who will describe not only the techniques that they have been using but some of the study's important findings.
A REVIEW OF WAVE MEASUREMENT AND ANALYSIS METHODS RELEVANT TO THE WAVE ENERGY PROGRAMME
Dr J A Crabb (IOS Taunton)

The paper is divided into two sections. The first is a brief and necessarily superficial review of existing wave measurement techniques; the section is largely confined to those methods which have shown themselves suitable for the routine measurements of waves at relatively remote offshore locations such as those currently of interest to the wave energy programme. The second section outlines a study currently in progress at the Institute of Oceanographic Sciences to estimate the directional properties of waves for initial device design purposes, and briefly describes some of the results obtained so far.

Wave measurement

It should be recognised that we are indebted in the main to two instruments for the majority of the measured wave data which we have at our disposal for use in the present stage of the exploitation of wave power.

The first is the shipborne wave recorder\(^1\), the general configuration of which is illustrated in Figure 1. Sensor packages installed on each side of the hull contain a gimballed accelerometer which measures the vertical component of the ship's acceleration, and a pressure sensor which measures the height of the water, \(A\), on the hull. The sum of the pressure signal and the doubly integrated accelerometer signal gives, after corrections for instrument response and hydrodynamic filtering of the pressure signal, the height of the water surface, \(A + B\), relative to an arbitrarily fixed datum level.

![Figure 1](image1.png)

Errors in measurement of wave height by this method could arise due to the rolling of the ship or an increase in apparent wave amplitude due to reflection from the hull; these are largely avoided by averaging the outputs from the sensors on each side of the hull.

The instrument was designed in the early 1950s, but it is still in routine and effective use on a number of selected light vessels and ocean weather ships. Wave data from OWS India, which have been important in the early stages of the wave energy programme, were collected by such an instrument. In addition the data returned by these instruments form an important input to the IOS general wave climate programme. A Mark 2 version of the instrument has now been produced with updated electronics.

The second instrument is the Datawell Waverider buoy, Figure 2, which is now widely used under a wide range of conditions. The instrument consists of a sphere 0.7 m in diameter containing a gimballed accelerometer, the signal from which is doubly integrated internally to yield the heave component of the buoy displacement. A compliant element in the mooring allows it to follow the surface waves. One possible mooring configuration is shown in Figure 3. Heave information is telemetered continuously to a receiving station via a VHF radio link. A typical receiving installation is illustrated in Figure 4; the photograph actually shows the IOS installation at the Hebrides. Using standard receiving equipment the telemetry range is approximately 25 km, and consequently the buoy must be installed within this distance of a fixed or floating structure. However, using more sensitive aerial arrays and receivers the range may be extended up to 50 km, making possible wave measurements at relatively remote offshore locations using shore-based receiving stations. An example of this is the IOS installation on the Island of Foula (run under contract to the United Kingdom Offshore Operators' Association), where the buoy is positioned 50 km to the west of the island and approximately 110 km to the west of the Shetland mainland.

![Figure 2](image2.png)

In addition to these two instruments there exist many other devices exploiting a wide range of principles for the measurement of waves. The majority are for use in shallow water or require to be mounted on fixed offshore structures. It is impossible to list these devices here, but further information on the range of types and the principles employed may be found in references 2 and 3.
The majority of the data collected by the shipborne wave recorder have been recorded on paper chart roll. It is usual to sample only a proportion of the data, usually fifteen minutes every three hours. In this way data storage and analysis problems are reduced whilst hopefully preserving effective monitoring of changes in wave conditions. Analysis of wave data in this form has been enormously facilitated by a technique developed by Tucker\(^4,5\) and modified by Draper\(^6\), based on the work of Cartwright and Longuet-Higgins, and Putz\(^7,8,9\). This allows the main statistical properties to be estimated by an abbreviated manual technique.

Statistics obtained in this way include the significant wave height, \(H_s\), and the mean zero crossing period, \(T_z\). The significant wave height is defined as four times the root mean square surface elevation and corresponds approximately to the average of the crest-to-trough heights of the highest one-third waves in the record. The mean zero crossing period is the average interval between the wave trace crossing the zero line in an upward direction.

Although the standard Waverider receiving equipment is supplied with a paper chart recorder, it is more usual to find these data being logged by digital recorders. A similar sampling scheme as that employed with chart recordings may be used. Stations of this sort run by IOS, including those to be run especially for the wave energy programme, record the incoming wave information for a period of 1044 seconds every three hours, and sample the signal every 0.5 seconds during that period. The magnetic tapes, which can hold up to forty days of data sampled in this way, are returned to the laboratory and subjected to an automatic translation and validation process designed to identify faults in the recorded data. An energy spectrum is then calculated for each of the records using a fast Fourier transform routine. Emphasis is placed on obtaining long series of reliable data with a view to establishing the characteristics of the wave climate. A one year series of data is normally considered the minimum requirement. In the case of IOS these results are then made available to interested users through the Marine Information and Advisory Service, and in due course a report summarising various aspects of the wave climate at the location is issued.

As well as the spectra, which are of direct use in many research and engineering applications, the characteristics of records are summarised in the same way as for the paper chart recorder. The quantities \(H_s\) and \(T_z\) are calculated as functions of the moments of the spectrum, defined:

\[
M_n = \sum_i E(f_i) \cdot f_i^n \cdot \Delta f
\]

where \(E(f_i)\) is spectral density at frequency \(f_i\) and \(\Delta f\) is the frequency interval between spectral estimates.

Then \(H_s = 4\sqrt{M_0}\) and \(T_z = \sqrt{\frac{M_0}{M_z}}\)

A further parameter, of interest in the wave energy context, is the energy period:

\[
T_e = \frac{M_{-1}}{M_0}
\]

At deep water locations this may be used to calculate the energy flux associated with a record:

\[
P = \frac{g \cdot g^2}{64 \pi} \cdot H_s^2 T_e
\]

\(p\) is the density of sea water.

### Directional measurements

The wave measurement techniques discussed in the previous sections give information only on the variation in water surface elevation at a point and pay no regard to the direction.
from which the waves approach. This variation in elevation arises from the combined effect of numbers of wave trains of different amplitudes and frequencies approaching from different directions. Knowledge of the directional characteristics of the wave field is important to the wave energy programme for two main reasons. In order to extract the maximum energy from the waves at a particular site a device should, if possible, face in the predominant wave direction; thus knowledge of the mean wave direction is important. The way in which incoming wave energy at each frequency is distributed amongst directions about the mean is also of interest in this same context, and is also of more general application. The directional spectrum allows many features of the sea surface shape to be derived, crest length being one such property.\(^{10}\)

As with the one dimensional wave measurements discussed previously the main requirement is for a long series of directional wave measurements at each location. Instruments capable of providing these data in deep water are rare, although the growing requirement for such information has led at least two commercial concerns into developing such systems based on the pitch-roll-heave principle first exploited by Cartright and Longuet-Higgins\(^{11}\). In this method a gyro-stabilised platform is housed in a discus-shaped surfacerequiring buoy and the pitch and roll angles of the hull relative to the platform are monitored. An inbuilt compass allows the computed directions to be related to geographical direction. A vertical accelerometer is again used to measure the buoy heave.

From these three channels of information estimates of the directional wave properties may be derived. The first step in the calculation involves computing the co- and quadrature spectra of pairs of these quantities. These may then be combined to form the first five Fourier coefficients of the angular distribution of energy. The coefficients may then either be used to compile a smoothed estimate of the directional spectrum, equivalent in this case to measuring the true distribution with a 130° angular resolution. Alternatively the coefficients may be combined to give just the mean wave direction at each frequency and the root mean square width of an assumed angular distribution function.

The effective directional resolving power of such a system may be improved by measuring further independent parameters of the surface shape; in particular information on the surface curvature in two directions at right angles enables four further Fourier coefficients to be calculated. The effective resolving power in this case is approximately 60°. Measurements of this type have been made using the so-called ‘clover-leaf buoy’\(^{12,13}\).

Instruments of both types have previously been used in research programmes but the attendance of a parent ship was required. Only recently in the UK Data Buoy 1 has the pitch-roll-heave principle been embodied in a system capable of unattended operation in remote locations\(^{14}\). Currently under development are similar but cheaper devices which will probably provide the majority of the measured directional wave data over the next five or ten years. Consequently it is these devices which are of most relevance to the wave energy programme.

There are however other promising techniques which are at earlier stages of development, two of which are mentioned here since they may, in the future, be of value.

The first is the synthetic aperture radar; a method in which a high-resolution picture of the sea surface is built up from a series of radar images obtained by viewing the surface in a direction perpendicular to the path of an airborne radar system. The equipment may be carried by an aircraft, as has been recently demonstrated on SEASAT-A, by satellite. A number of uncertainties and disadvantages currently attend this method. The incident microwave radar signal is returned by Bragg scattering from the short (centimetre) capillary waves which are almost always present on the surface. The characteristics of the underlying gravity waves, in which we are interested, can only be accurately determined if the relationship between the two wave types is reliably known. Uncertainty in this area means that the height of the gravity waves is not readily obtained and could also lead to ambiguity in wavelength measurements. In addition to this, the present requirement for regular measurements at a particular site could be costly to satisfy using airborne systems.

The second method is also a radio technique in which an area of the ocean surface is illuminated with high frequency radio waves with wave length of the same order as the gravity waves. The Bragg scattered energy is received and its Doppler spectrum is used to indicate the direction in which waves of a particular frequency are travelling. Such a technique is currently being developed in the UK\(^{15}\) and has already demonstrated its ability to measure mean wave direction. In similar developments in the United States\(^{16}\) attention has been paid to the possibility of processing that portion of the Doppler spectrum which corresponds to the signal having been scattered from one wave train to another at right angles, in the manner of a corner reflector, before being returned to the receiver. This higher order region of the spectrum contains information on the distribution of energy with direction, and it may be possible to derive the directional spectrum. Methods such as these, if sufficiently developed, offer the prospect of economical routine operation.

These and other techniques may be found discussed in a useful review paper by Panicker\(^{17}\); an extensive reference list is also included, see also references 18, 19, 20 and 21.

Synthesis of directional spectra

The lack of relevant directional data has led to various attempts to estimate the directional properties of waves using only information currently available. One such method has been developed by Hogben\(^{22}\) and is described elsewhere; another is being developed within IOS and is outlined in this section.

The method requires a long time series of good quality wave data covering a period of at least one year. Such a data set is available from the IOS Waverider installation (supported by the Departments of Energy and Industry) at South Uist in the Outer Hebrides. From approximately 2,700 wave records collected during the first years of operation, a more manageable sub-set of approximately 400 was selected. Selection was made on the basis that measurements of wind speed and direction, made simultaneously with the wave records at a nearby shore-based meteorological station, should conform to the known long-term distribution of winds in the area. Thus an attempt was made to select a sub-set of wave records statistically representative of the long-term wave conditions. The energy spectrum corresponding to each wave record was calculated.

The first step in converting each of these spectra into a directional spectrum is to divide the one-dimensional spectrum into two sections corresponding to locally-generated wave energy and advected swell energy. It is necessary to treat these two components separately since, in general, the direc-
tional characteristics of local sea and swell will not be the same.

The division was accomplished by adapting empirical wave forecasting formulae to permit the local wind sea on each occasion to be predicted from a consideration of the associated wind conditions. In particular the lowest frequency component which could be regarded as belonging to the local sea portion was identified; all energy at lower frequencies was regarded as being due to swell.

Directional properties may then be ascribed to the wind sea portion of the spectrum by appealing to existing empirical formations describing the relationship between wind speed, wave frequency and the distribution of wave energy with direction. The formulation which will be used in this case is that due to Mitsuysasu[23].

Attributing directional properties to the swell portion of the spectrum necessitates identifying the source of swell generation on the meteorological charts. The mean direction and directional spread of the swell may then be estimated from the bearing and subtended angular width of the generating area. (This part of the method is currently being developed.) An estimate of the directional spectrum is then produced by recombining the wind sea and swell components.

Preliminary results

Although this exercise is still in progress certain results are available which illustrate some significant aspects of the wave climate to the west of the Hebrides.

The selected set of 400 one-dimensional spectra have been provisionally adopted by Technical Advisory Group 2 as defining a reference wave climate for the area. The set contains spectra with a wide variety of shapes; very seldom do they resemble any of the accepted standard spectral forms. This is in the main due to the persistent presence of swell at this location, giving rise to a high proportion of multi-peaked spectra.

The mean power level calculated for the selected spectra is 48 kW/m, and this should be close to the annual mean power level at this site. The figure is consistent with estimates arrived at by other means. Power calculations performed separately on the wind sea and swell components of each spectrum indicate that approximately 65% of the annual mean power is attributable to swell.

Recently a second buoy has been installed some 11 km to the east of the original buoy. Figure 5 shows the result of a comparison of wave power levels measured at the two sites for a period of 26 days in December 1978. During this period
moderate winds blew exclusively from the easterly directions; consequently the majority of the wave power during this period was probably due to swells approaching from the west.

The reduction in power between the original buoy site 16 km from shore and in 42 m of water, to the new site, 5 km from shore in approximately 15 m, is seen to be approximately 60%. The slope of this line, 2.5, compares with a slope of 3.1 obtained during a similar period in August and September when winds were moderate and largely westerly. These figures are probably representative of the average power reduction to be expected. The true figure, however, will only be known when a long series of comparative data has been analysed.

References
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REQUIREMENTS FOR WAVE DATA
Dr D Mollison (Heriot-Watt University)

My task is clearly to describe the remaining aspects of TAG 2's work, and perhaps to look to the future. Fortunately, to help me in this task there was a syndicate meeting held during the Workshop to discuss wave data, and I shall follow its report and deal with the Wave Energy programme's requirements for data under three headings: (1) Resource Assessment, (2) Directional Properties and (3) Firmness of Power. There is actually a considerable overlap between these, but they provide a reasonable framework within which to review the programme's requirements and what is being done to fulfil them. I shall conclude by discussing the principal difficulties which remain to be overcome.

Resource Assessment

The power density in deep-water waves is proportional to the height squared times the period (\( P = KH_{rms}^2T_e \)), and the efficiency of wave power devices varies with both height and period, so the minimal data requirement would seem to be a joint distribution for these two variables: an example of such a "scatter diagram" is shown in Figure 1.

With this kind of information, device teams can have a first stab at estimating the power they might get out with their device. Here (Figure 2) is an example from the Edinburgh Wave Power Project showing the effect on output of varying the diameter and torque limit of Salter ducks.

Although without costings you can't get very far with this, you can draw simple conclusions such as that if you are going to have power machinery with a torque limit of 0.5 units, it would be silly to have a 15 m duck because it performs no better than a 12 m one.

You thus get first estimates of output, and you may also get a first stab at the problem of extreme conditions. If I can go back to the scatter diagram (Figure 1) I think the question here is perhaps one which will have to be thrown back to the device teams: do the extreme conditions for your device occur in the outer part of the scatter diagram (A), in which case design for survival is extremely difficult since it involves the usual impossible job of predicting very rare events? However, with some devices, extreme stresses may occur in steep waves of intermediate period (B); if that is the case the problem is much easier, since little or no extrapolation beyond observed conditions is required.

Directional Properties

The second and most difficult requirement for information concerns directional properties.

In order to examine device behaviour and thus accurately determine how much power we can get out, we need to have an idea of how devices behave in directional seas. Now a typical nasty sort of sea that the scatter diagram doesn't tell us much about is one where you have a wind sea and a swell coming from different directions with a sizeable angle between the two, and the frequency spectrum perhaps divided up into a rather sharp long-period part (the swell) and a rather more spread short-period part (the wind sea); it is clearly unsafe to extrapolate from simple device tests to such a complicated sea.

John Crabb has already described a method for the synthesis of directional spectra from wind and wave information. A quicker alternative, though possibly less accurate, is the method developed by Dr Hogben of the National Maritime Institute; and since he is in the audience, if I describe it wrongly he will be able to correct me. This makes use both of the height-period scatter diagram you may expect to have for a particular site (perhaps only from chart records, not necessarily superior digital information such as we are getting from IOS for South Uist), and also a scatter diagram of height against wind speed (Figure 3). Wind-wave scatter diagrams for a wide variety of sites are similar in the way in which height (H) increases with windspeed (U), but with a considerable scatter about the average height associated with a particular windspeed. This pattern prompts the following recipe for dividing a record, with energy proportional to \( H^2 \) into its wind-sea \( (H^2) \) and swell \( (H^3) \) components. The wind-sea is fitted from the increasing trend, so that \( H^2 \) is proportional to \( U^{1.4} \) approximately, while \( H_3 \) \( (\sqrt{H^2-H^2}) \) is independent of the windspeed; the distribution of the swell height \( H_3 \) is thus assumed to be given by the scatter of wave heights which occur with zero wind velocity. To complete the recipe the wind-sea is given a directional spread either side of

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**Figure 1:** Joint frequency distribution, in parts per 1000, of wave height \( H_{rms} \) and period \( T_e \) at OWS India, with contours of power in kW/m. (For the meaning of the areas marked 'A' and 'B' see text.)

**Figure 2:** Predicted average power output of Salter ducks at South Uist, as a function of torque limit, for diameters 10, 12 and 15 m.
chosen at random from a family of swell and wind-sea directions, but clearly if you have more information about a wind-sea and swell component, is the determination of the frequency of very low power levels should be more radically angle between the two; in a preliminary way this is just
Strictly speaking, firmness of power, as referred to earlier by
\[ xZ \]
the wind's direction fitted from a standard formula such as Mitsuyasu’s, while the swell is assumed to be more narrowly spread about its principal direction, I think Dr Hogben would agree that the biggest problem, apart from the separation into wind-sea and swell components, is the determination of the angle between the two; in a preliminary way this is just chosen at random from a family of swell and wind-sea directions, but clearly if you have more information about a site you should be able to do better. This brings out a point to which I will return, which is that such models require validation of some kind, or at least calibration, before we can adopt them for routine use.

**Firmness of Power**

Strictly speaking, firmness of power, as referred to earlier by Mr Russell, concerns the frequency of occurrence of low power output levels, and the possibility of reducing this frequency by mixing outputs from more than one site. The reduction in variability which can be expected from mixing two sites with independent outputs is illustrated in Figure 4. If the sites have the same proportional variability (ratio of standard deviation to mean, \( \sigma/u \)), the variability of the mixture will be minimised by installing plants with equal mean outputs; \( \sigma/u \) will then be reduced by about 30%. The frequency of very low power levels should be more radically reduced, however: while for a single site the frequency curve is approximately constant for lower power levels, for the mixture the frequency of levels below \( x \) will be proportional to \( x^8 \) (shaded area in Figure 4). Michael Stoaling, of the Edinburgh Wave Power Project, has found that sites west of the Shetlands and in the Celtic Sea behave approximately in this fashion; in particular, within each season their power levels are approximately independent.

The heading of ‘firmness of power’ can, speaking loosely, be understood to cover all questions of variability of the resource, both spatial and temporal, and ranging in scale from second-to-second to year-to-year. To begin with small-scale variability: here we are concerned with the statistical distribution of instantaneous stresses, and the possibility of smoothing the power output of a device (see Figure 5) over either space or time so as to provide a more steady input to the electricity grid. Here there are two simple points to be made: the statistical properties of wave records with a given spectrum can be determined theoretically, and vary little between records with the same height and period. Secondly, the effect of smoothing over the period of time in which a given number of wave passes is similar to that of smoothing over a length of devices corresponding to the same number of crestlengths.

At the other extreme, year-to-year variation, we can make use of data for winds, which are available for much longer periods than for waves. Figure 6 shows hindcasts for monthly average power levels at South Uist based on such wind data, which in this case are available back to 1965 (prior to that a different kind of anemometer was used at the relevant site, Benbecula Airport, which poses difficulties of calibration). This hindcast reveals that 1976-77, the first year for which the Waverider was at South Uist, had probably the lowest average power among the twelve years considered; the second year was much closer to the average. It also reveals considerable year-to-year variation, with standard deviation of 25 to 30%. One implication of this is that there is a statistical limit of about ±8% on the accuracy with which we could determine the long term average power level even if we had twelve years of perfect wave data (nor does this make any allowance for possible slow climatic changes). With this caveat, it is encouraging to find that this method yields estimates for the average power level which are in good agreement with the IOS method described by John Crabb, which uses long-term wind data in a quite different way.

The last model I want to talk about, and perhaps the most important, is the Meteorological Office’s wave forecasting model developed by Brian Golding, which calculates waves not just at one point but for waters all round the British Isles. This uses wind data provided by the Meteorological Office’s routine weather forecasting model to calculate a directional spectrum for each point of a grid with 50 km spacing covering a wide area around the British Isles, which is in turn linked up to a 300 km grid covering the entire North Atlantic, so as to deal with swells originating at great distances. The model which is being tried out at present uses fairly crude wave spectra, divided into twelve directions (at 30° intervals) and six frequency components. Calculations proceed in half-hourly time steps: if the component for any direction and frequency is less than the maximum local wind would generate it is augmented towards that level; between time steps each component travels independently in its own direction and at its own velocity. This algorithm involves considerable simplification, but the greatest errors are those due to uncertainty in determining the wind field.
Figure 6: Monthly average power levels at South Uist, as measured by Waverider buoy (+'s), and fitted from wind data (solid curve; the dashed curve represents the 12-year averages for each month). (Note: this figure shows a preliminary fit based on only the first of the two years of wave data for this site.)

Figure 7: Comparison of Meteorological Office model's predicted power levels at South Uist (dashed line) with actual levels as measured by Waverider buoy (solid line), for November 1977.

Such a model, if at all accurate, is extremely useful in a number of ways. It provides routine directional spectra, with a breakdown of each into wind sea and swell. It can be used for forecasting waves up to one or two days ahead, with some loss of accuracy due to replacing measured winds by forecast ones. Thirdly, it provides a general view of the spatial variation and correlation around our shores which could be of great value both in comparing possible sites and in investigating firmness of power.

To date, the only checks on the accuracy of the Meteorological Office model are in respect of point measurements of height and period. For instance, Figure 7 shows a comparison of its earliest predictions for its grid point closest to South Uist with the Waverider at that site. The model predicts rather higher power levels, but otherwise fits quite well, and it agrees in predicting a very large proportion of swell at South Uist. Of course it is not at its best in predicting waves at inshore sites because a 50 km grid is too coarse to describe the shoreline adequately; it may be worth considering funding a finer grid model for inshore areas of interest if the model proves accurate for offshore waters.

Future wave data programme

At the syndicate meeting on wave data to which I referred at the beginning of my talk, it was felt that the availability of data, except for directional data, was satisfactory for present needs. The availability of skills to analyse existing data was more of a problem. Government institutions, such as IOS and NMI, find it difficult to employ people on projects of limited duration, and people with the necessary background are scarce.

It was agreed that numerical hindcasting or forecasting models and the data collecting programme are complementary rather than competitive: the models allow extrapolation from data, but require data for validation and calibration. It was also agreed that the top priority was the requirement for directional data. We should try to obtain this both from directional buoys, and from radar overflight techniques.

There remain however the difficulties of making use of the existing large quantities of data, and applying them to the problems of engineering design. Perhaps this problem will always be with us, since good statistics requires a rare combination of qualities: mathematics and common sense.
DISCUSSION

S H Salter (Edinburgh University)
I would like to say to John Crabb that measuring data with the reliability that has been achieved off South Uist is really quite an extraordinary achievement. They have been using complicated electronics with a VHF radio, gimbals and gyros with 90% availability in very difficult conditions. I think IOS and Datawell have done a very good job and perhaps you could draw the attention of the civil engineering community to what can be done with skilful electronics.

Dr J A Crabb
Thank you: I'll pass those comments on to the people concerned at IOS.

R T S Baker (Sheffield Polytechnic)
Yesterday Peter Clark assumed only the Hebridean coast and the south-west of England; today we have heard about measurements in other areas. Without pressing the forecasters too hard at this stage, could we take it that the researches described today might possibly enlarge the potential of wave power in various places? Might we have to keep an open mind on the figures we have been given by Peter Clark and others?

R C H Russell
The answer must be "yes", mustn't it? These data buoys like Kinnairds Head are not yet installed, and obviously there may be a chance that RPT have underestimated the potential. You have made a good point.

Dr D Mollison
On several maps, and maybe on previous consideration by RPT themselves, there has been an assumption that a full exploitation of the resource would have a line across the Moray Firth, off the north-east of Scotland. I think there is general agreement that it is unlikely that the waves are worth having once you come further south to the shallower North Sea.

Dr N Hogben (National Maritime Institute, Feltham)
First, I confirm that Dr Mollison's account of the NMI method of directional wave climate synthesis gave a good indication within the limits of the time available of the basic principles. Those interested however may like to know that full descriptions and numerical results of sample applications may be found in NMI Report No R45 which also reports some promising new developments relating to the prediction of wave statistics from wind statistics. The main point I wish to make however is to emphasise the importance of effective validation for climate synthesis and hindcasting models to make the best use of available data resources. A number of speakers including Sir Hermann Bondi have expressed concern about the apparent lack of adequate data on sea conditions and specially on the directional properties of the waves. It is indeed true that data in terms of directional spectra obtained directly from measurements are almost non-existent. Supplies of simpler forms of data which can be used for hindcasting or statistical synthesis of directional climate are much more plentiful however and would go far towards meeting many of the present engineering requirements if such methods can be adequately validated. Report R45 includes a review of available data and here I will only cite a few illustrative numbers indicating the scale of the archives of visual wave and wind statistics held by meteorological agencies. Visual estimates of wind speed (Beaufort number) and direction have been collected from ships at sea since 1854 and estimates of wave height, period and direction since 1949. Mr Russell referred to the book 'Ocean Wave Statistics' which presents data based on about one million sets of observations mainly concentrated on world shipping routes. It should be emphasised however that the World Meteorological Organisation hold far more data than this and the US National Climatic Center has compiled a set of magnetic tapes (also now available at the UK Meteorological Office in Bracknell) which carry about 50 million sets of observations all of which include wind parameters and about a third of which include wave parameters. These cover most sea areas of practical interest throughout the world and are not confined to shipping routes. In UK waters the density is of the order of several thousand observations per one degree square. In the present context it is of particular interest also to note that validation studies of the visual wind data in comparison with anemometer measurements have been carried out on a massive scale by R G Quayle of the US National Climatic Center. Cumulative frequency distributions based on over 200,000 measurements and about 600,000 observations covering the North Atlantic, the North Pacific and the Indian Ocean showed that observations of Beaufort number are a remarkably reliable basis for derivation of wind speed statistics. These results clearly add greatly to the value of the visual wind data archives and provide strong encouragement for work which is being done at NMI, as described in our Report No R45 on the derivation of wave statistics from wind statistics. It is of course also important however that wave climate data derived from hindcasting or statistical synthesis models should be validated by comparison with good quality instrumental wave data. I therefore make a plea that more attention should be given to use of the relatively scarce and very costly sets of wave measurements which are being collected, for calibration and validation of predictive models which can unlock such massive archives of additional data offering more systematic coverage of potential deployment areas.

G H Mellar (Centrax Ltd)
I am a little confused by the different references to swell. Could one of the speakers give a simple definition?

Dr J A Crabb
In my context, swell is simple wave energy which was not generated by local winds over the previous 24 hours. I am not putting that forward as a general definition of swell, but I think it conforms to most people's picture of what swell is; it's generally regarded as having been advected from distant generating sources. One relevant point is that there is no implication about the frequency of such energy in general.

Dr F J P Clarke (Chairman)
If I were to say that swell would be from storms say 500 to a few thousand miles away, would that be about right?

Dr J A Crabb
There are cases when swell can come from very much closer than 500 miles, depending on the meteorology.

R M O'Flaherty (Electricity Supply Board, Dublin)
I have five short points. First, it seemed from the photograph that you were using a standard Datawell Waverider mooring: can you confirm that? It also seemed that you are not using a Datawell antenna system: I would like you to comment on that. I would also be interested to know whether or not it is a Datawell digital logging system. What frequency of buoy and mooring replacement did you operate to? Finally, are there any general figures from the Meteorological Office model for the probable swell content off the west coast of Ireland? You have a figure of about 65% at the Hebrides, and I just wonder whether it is significantly different off the west...
Dr J A Crabb
I'll deal with the first four points and hand the last one over to Denis. The Datawell mooring that I showed is not actually the one we use at South Uist; we have designed our own for that particular location on which I can give you information if you require. The antennae I showed were special directional ones which we employ on the Island of Foula because of the extreme range of the Waverider at that site but generally we do use the standard Datawell antenna. The logger is not a Datawell logger. The buoys and moorings are serviced at approximately six-monthly intervals and I believe it is the case (although it is not really my responsibility) that the mooring is discarded each time.

Dr D Mollison
The Meteorological Office prediction for swell at South Uist is for very precise data, improving perhaps on this 20% variable do use the standard particular location on which I can give you information if you require on the Island of Foula because of the principle the Meteorological Office model could well tell you something about that; however I am not certain whether the 50 km grid, as opposed to the coarser 300 km grid which is used for open Atlantic, extends as far as that.

Prof D T Swift-Hook (CEGB)
The first thing that I thought might be interesting to say in this company is that there are strong analogies with the wind power programme where similar things are being said. Surprise is being expressed that the amount of data isn't as much as people would have thought, or as people from other areas of the wave business would tell you. The second point I wanted to make is that it's clearly a very great problem to get significant accuracies with the year-to-year variations and so on. If we are really worrying about the precise amount of power available which would have an effect on the precise costs of devices, then we would perhaps be justified in going for very precise data, improving perhaps on this 20% variable annual average or 8% accuracy from 12 years. But in view of the prices we heard yesterday, where you are looking for order-of-magnitude changes, it seems to me you only need to get within some fraction of an order of magnitude on the accuracy of your data. So I would like to ask the question: are there not cheaper and quicker techniques that would get in the data that we need to the accuracy we need, which is not very great. Finally, the purpose that we want to put most of the data to (by no means all but certainly most), is just that of measuring exceedances; that's to say, we want to know how much of the time the power is at what level. If you happen to feel you know the shape of that exceedance curve, you only need to measure one or maybe two exceedances; I wonder whether there are not simpler methods of just recording the number of times the wave height exceeds a certain level. Perhaps there are wave devices, transducers, that would be simpler and more robust and more reliable than doing what we clearly do at the moment, which is virtually to measure how the wave height varies at every instant of time and then throw most of that information away to do an exceedance plot.

Dr D Mollison
As a statistician I am extremely unhappy about the way people, whether in calculating the probability of failure for a nuclear power station or for an oil platform due to an extreme wave, take parametric models and fit them to tails of distributions and talk about probabilities of 1 in 10^8 or once every 100 years. Also a second point with wave power that I was trying to make is that I am not so certain that for some devices what we really are interested in is the extreme highest wave, it may well be that what cracks up your wave power device is a very fast growing, very steep sea of period 9 or 10 seconds, something relatively modest like that.

Dr J A Crabb
Wave data collection at present is not expensive really in relative terms. I would argue strongly against limiting the equipment you put in the sea simply because it satisfies a particular requirement at the time. Someone is going to want that data for something else in the future, so we are obliged to do the best we can.

Dr D Mollison
Again as a professional statistician I would say that it is very silly to limit yourself if you don't have to, with so many uncertainties in the future and many people other than wave power people interested in getting good data; the more flexible your collection and the more complete it is the better.

Prof Sir Hermann Bondi (Department of Energy)
From what I have heard I am glad to be able to say that I am very much encouraged after my rather more critical remarks yesterday. I am particularly interested in the question of validation of models which would allow access to an ever wider range of data, which Dr Hogben spoke of. Where I still feel a little uneasy is, I think, in relation to remarks just made from the platform - I agree with those remarks, and I think they reflect the same unease - that the transfer function from the raw data to what is utilised in any particular type of device still seems a little primitive. The transfer function to disaster, which may put survival at stake, is still very very little help. In those circumstances one certainly needs the raw data, but one does hope that before very long we can exploit them more fully than now.

R C H Russell
I'm glad from a personal point of view to have a bit of support for my view that probably we are collecting data at about the right pace, although there is pressure from various sources to speed it up. It is right that data should be collected at a sophistication well in advance of what is being used - and that is what we are doing. I doubt if many of the device teams are yet ready to use a year's accurate data on the South Uist wave climate which will very shortly be available; most of them, I think, are very content with the data which is available at the moment. I think we are making enough progress. On the 8% accuracy of data, this is not a matter of accuracy of measurement -- the average power level really does vary from year to year. For the statistical question of whether one point on the curve is enough for a Gaussian distribution, I'll pass it over to Denis.
Most but not all of the developments and activities that have been described to you yesterday and today have been funded either completely or partially by the Department of Energy. This is of course completely appropriate as the Department of Energy and the Wave Energy Steering Committee are controlling what in effect is a national programme in wave energy. What then, you may ask, is SRC doing, funding work in wave energy? The Science Research Council is a part of the Department of Education and Science, charged with supporting research in science and technology at universities and polytechnics and making grants for post-graduate education and training. Part of its function is to consider important topical fields of activity and to determine the need for any specific action which in its opinion should be taken to encourage academic interests and activities.

One area in which SRC has taken such an initiative is the field of marine technology; however one might define marine technology, you would probably all agree that wave energy forms a part of that field. That indicates why SRC has an interest in the subject. It is perhaps not unknown for different agencies of government spending that have similar interest in a subject area to pursue and to spend money without any consultation; that's not the case in this subject area, I am glad to say. SRC and the Department of Energy do have a dialogue at many levels on many subjects and they have a dialogue in the field of wave energy. In the early part of 1978 SRC found itself funding a very small level of work on wave energy, but there was a considerable increase in academic interest; it seemed appropriate and necessary that we should develop a closer understanding with the Department of Energy about our role if there was one.

We have developed that understanding; effectively the Department of Energy spends money wherever appropriate to accomplish its fairly immediate objectives. That may or may not include universities, but there is a role for academics to make a supplementary contribution and this is through a supplementary programme run by SRC in wave energy; by and large it includes the more speculative work and more fundamental work which is of less immediate interest to the Department of Energy programme. It's relatively small; the total sum of money we are providing in the field at the moment is approximately £150,000, with annual expenditure of about £60,000. Yesterday you heard about work going on at the University of Lancaster and Queen's University, Belfast, both of which are receiving funds from SRC; the next few presentations will tell you more about the work we are funding.
THE SUBMERGED CYLINDER WAVE DEVICE
Dr D V Evans (University of Bristol)

It has been shown theoretically\(^1\) and can be confirmed experimentally that when a submerged circular cylinder rotates on an eccentric axis parallel to its own, the waves produced on the free surface travel away from the cylinder in one direction only, being the direction of motion of the top of the cylinder at the top of its orbit. Theory\(^2\) has shown that the reverse is true, namely, by loading the cylinder with appropriate spring and damper forces all the energy can be extracted from small amplitude regular incident waves. Experiments\(^3\) using the Salter pitch-heave-surge rig, developed for testing the 'duck' device, have confirmed the theory for small waves and have predicted acceptable efficiencies in moderate waves. Thus Figure 1 shows the variation of efficiency of power absorption as a function of wavelength \(L\) non-dimensionalised with respect to the cylinder diameter \(2a\), for a range of wave amplitudes \(A\) non-dimensionalised with respect to the cylinder radius. It can be seen that for very small wave amplitudes the cylinder is extremely efficient with good agreement between the experimental points and the solid line representing the theoretical predictions, whilst the efficiency falls off at larger wave amplitudes. Details of the experimental procedure and further curves showing the variation of efficiency with depth of submergence, together with a full theoretical treatment, can be found in reference 3.

The Salter rig, while permitting arbitrary spring and damper loads to be applied to the cylinder in the horizontal and vertical direction so that a direct verification of the theory is obtained, has one limitation. Theory suggests that the lighter the cylinder, the broader the bandwidth of the efficiency-wavelength curve becomes. This is borne out by the dotted curve in Figure 1 which represents the theoretical efficiency for a genuinely neutrally buoyant cylinder. The experimental points and the solid line include allowances for the unavoidable horizontal and vertical inertia of the supporting framework of the rig which were of the same order of magnitude as the cylinder mass. In addition, the rig, which was designed specifically for modelling the behaviour of Salter's 'ducks' on moving backbones, does not provide a model for a realistic complete cylinder system. Indeed, one of the major problems with the cylinder, as with all wave-energy devices, is to establish a stable reference frame relative to which the device can move, while at the same time allowing efficient power absorption from the induced motion of the cylinder. One way to achieve this is as follows. The cylinder is constructed to have positive buoyancy and is held down in the required position below the surface by four neutrally buoyant cables, two at each end. The cables are fastened around cable drums at their lower end. These cable drums are torsionally spring loaded such that tension is maintained in the cables to keep the cylinder down, and in flat calm seas the upward force on the cylinder due to its buoyancy will be exactly equal to the downward tension of the cables due to the torsion springs in the cable drums. When the cylinder is forced by a wave to move in a direction such that the tension in a cable reduces then the cable drum will wind on the cable to 'take up the slack', ie the spring will do the work. When the cylinder is forced to pull on a cable its drum rotates and so work is done on the spring. The power take-off mechanism may also be placed in the same housings as the cable drums on the seabed.

The experimental programme in Bristol, which started in February 1978 and is funded by a grant from the Science Research Council, uses this mooring system as the basis for a detailed study of the behaviour of the cylinder under a variety of conditions. Figure 2 shows how the loading of the cylinder can be controlled by means of printed armature motors with integral tachometers. Leaf springs are used to ensure that the system resonates with the frequency of the incoming wave. Strain gauges in the cables close to the cylinder measure the oscillating forces on the cylinder (Figure 3) which together

![Figure 1](image1.png)

![Figure 2](image2.png)
with velocity measurements enable the power absorbed by
the cylinder to be determined. The experiments will determine
the efficiency of power absorption of the device as a function
of amplitude and frequency of the incoming waves, depth of
submergence, and buoyancy. Subsequent tests in a wider
(0.75 m) wave tank will enable the influence of aspect ratio
and spacing between adjacent devices to be predicted while
the new rectangular tank (8 m x 3 m) will enable tests in
short-crested seas to be made. Tests in random seas will also
be carried out. A concurrent feasibility study of a full-scale
device is also under way in co-operation with an industrial
organisation.

References

3. Evans, D V, Jeffrey, D C, Salter, S H and Taylor, J R M
DEVELOPMENT OF THE SUSSEX WAVE-ENERGY CONVERTER
Dr J O Flower and Dr G F Knott (University of Sussex)

The operating principles of this fully-submerged device have been derived from theory relating to cylinders as first described by Evans[1]. Literal implementation of this theory requires a cylinder to be coupled through mechanical elements to an inertial reference so that its motion in response to waves is physically regulated, leading to an absorption of wave energy. Our device is likewise cylindrical but is constrained to remain stationary while internal mechanical elements regulate the flow in the neighbourhood of the cylinder to absorb the wave energy. Here, theory by Ogilvie describing the forces on immersed cylinders(*) assisted in the understanding of local wave interaction. In particular it could be deduced that regular incident waves induce a pressure wave on the surface of an immersed cylinder which rotates around the circumference in synchronism.

A first scheme was devised in which a deformable layer composed of fluid-filled bags was laid around the surface of a stationary rigid cylinder entirely enclosing it. The induced pressure-field sweeping around the cylinder would compress the bags in turn, forcing fluid to be transferred between them through ducts and fluid machinery. The arrangement of the bags and the resonant transfer of fluid would be so arranged that the external boundary of the device would remain circular as it 'deformed' and orbited, thereby conforming to Evans' rigid-cylinder conditions for optimum-energy capture.

While this scheme is still being considered, an alternative scheme which dispenses with the flexible materials is being developed. This idea has a yet more tenuous approximation to the original theory, but is more convenient to engineer. Here it is assumed that the motion of a cylinder interacting with waves can be reproduced by the cumulative effect of a number of discrete pulsating sources and sinks distributed around the periphery of a stationary cylinder; from which it follows that the 'source' field should be able to match the wave-induced field in such a way as to transfer energy.

In effect the design reduces to that of the 'flexible-bag' absorber without the bags, and with a complex local flow at

Figure 1: Cross-section through the three-phase laboratory model showing the arrangement of the pistons and cylinders. The third piston is omitted since it can be shown in principle to be mechanically redundant.

Figure 2: View of the cylindrical frame showing the location of the working section.
Figure 3: Illuminated view of the interior from outside the tank.

Figure 4: The crank mechanism.
matched and in tune with prevailing wave conditions the fluid sources will resonate and efficiently absorb energy.

When working in such a mode three-dimensional fluid-dynamical effects become highly significant and a very large percentage of the total power incident upon the complete structure can be absorbed by mechanically-moving parts whose geometric extent is quite small compared to the overall structure size.

The most obvious way of combining the individual pistons to provide a total power take-off is via a crank and connecting-rod mechanism. This would be entirely suitable if monochromatic waves of fixed amplitude existed at sea. One is forced to consider, however, the random nature of sea-waves and under these conditions independent piston arrangements would appear necessary to achieve resonant operating conditions. An additional problem is, of course, the need to anchor the whole structure in a satisfactory way.

A laboratory-scale model of such a device has been constructed to demonstrate the above working principles and tests have been carried out in a small wave-tank. This demonstration device consists of a 20 cm diameter aluminium tube fixed athwart the wave-tank, (Figure 2).

Three circular intersecting ducts are bored radially into the perspex mid-section of the cylinder inclined at 120° to each other. Neutrally-buoyant pistons operating within them are mutually connected by rods to a central crankshaft which is in turn coupled to a small DC motor, (Figures 3 and 4). The DC motor can be used to apply torque in either direction thereby acting as a motor or generator for power control. In response to incident waves the pistons move reciprocally in sequence, turning the crankshaft evenly at the wave-frequency.

With reasonable tuning the system can – aerial-like – absorb more than 80% of the wave-power incident on the device and even when poorly tuned the system can absorb 30% of the power, as reported more fully in reference 3.

Since its operation is at present constrained by the fixed-crank arrangement, a figure for bandwidth cannot sensibly be derived from the experiments. However, in its improved form its bandwidth will be related to that of Evans’ theory, with some inevitable reduction of, at most, a factor of 2 due to the resonant source principle.

With this sort of mechanical device the losses are large at this scale. Mechanical friction is high and viscous effects are significant. No attempt has been made at this stage to produce an 'optimized' design since the data necessary are practically non-existent at this stage. In fact much of the current work is aimed at obtaining basic information, using simpler structures than that described, which will not only be applicable to Sussex-type devices but to other types which effectively operate by the transfer of fluid under resonant conditions, eg the Vickers and NEL devices.

In conjunction with the above, specifically aimed at device development, work is proceeding on a more general front in attempting to improve instrumentation and experimental technique, flow-visualization and computer-processing of data both from laboratory experiments and from real-sea data.

References
The first point that I must make is that I will be describing a programme of work which I am carrying out jointly with my colleague, Dr Collings. Secondly, I should point out that the programme in which we are engaged has been running for only a few weeks so that I shall be talking more about what we are proposing to do than what we have actually achieved. We are investigating a new design of air buoy and also a new form of self-rectifying air turbine. At present, we are working with small-scale models. We think that a full-scale version of our air buoy would have a capacity of about a thousand cubic metres, in other words, it would be about the size of the average house and would produce on average about 100 kW of electrical power. If the approach turns out to be feasible a large number of buoys would be required and we feel that unit costs could be minimised as a consequence of large-scale production. Our programme objective is to arrive at some estimate of the commercial feasibility of this particular approach to wave power.

Figure 1 shows a cross-section of the air buoy we have under investigation. As you can see it has two air chambers, one at the bow and one at the stern. The buoy will be moored so that it faces the direction of the incoming waves. The waves, of course, arrive at different frequencies and we are studying the feasibility of absorbing a high proportion of the incident wave energy by having systems within the buoy which resonate at different frequencies. Firstly, we can arrange for the water level in each chamber to oscillate at a different frequency. This motion drives air in and out of each chamber through a passage in the top. A full scale buoy would have an air turbine in each passage which would drive a generator.

In addition to the motion of the water level inside each chamber we can arrange for the buoy to have a pitching motion. In Figure 2 the front chamber is oscillating up and down with the rear chamber stationary in the water. At a different wave frequency the rear portion of the buoy moves up and down as is illustrated in Figure 3. These pitching motions drive air in and out of the front and rear chambers. In addition we can have the buoy moving bodily up and down in the water and this can occur at yet another frequency. Hence we have five different systems resonating at different frequencies and we will arrange for these to cover the frequency range of the incident wave motion. In a real sea a number of frequencies would be superimposed and we want to see how a buoy of this type will behave under these conditions. We now have to consider the air turbine which we want to rotate always in one direction as the air flow...
fluctuates and reverses. We are investigating the feasibility of using a Savonius rotor for this purpose. This type of rotor has been in use for some time as a windmill and is illustrated in Figure 4. The rotor spins about a vertical axis and always rotates in the same direction whatever the direction of the wind. We have put this type of rotor into a duct (Figure 5) and are now looking at ways of improving its efficiency. Clearly the air blowing on the convex part of the rotor is less useful than the air blowing on the concave part, so we are looking at the effects of different air inlet and outlet arrangements. One arrangement is shown in Figure 6. We are also starting to investigate the effects caused by changing the shape of the rotor. I have a short length of film which I am going to show you now and this illustrates some of the work which we have been doing.

The wave tank is not particularly elaborate. At one end there is a wave generator which can produce either uniform or random wave motion. The model air buoy which we are using is constructed mainly from perspex sheet. We have tested the buoy immersed in the tank and fixed to a rigid frame. At one frequency resonance occurs in the front chamber; changing the wave frequency produces resonance in the rear chamber. We have also tested the buoy floating freely in the tank. Again, at one frequency we see the rear of the buoy almost stationary with the front chamber oscillating up and down; changing the wave frequency produces a similar effect in the rear chamber. We can adjust the natural frequency of all the resonating systems so that we can extract energy over the whole range of wave frequencies.

We are also using a small wind tunnel in our attempts to improve the design of the Savonius rotor for our purpose. We are investigating the effects of the geometrical form of the inlet and outlet ducts and the design of the rotor itself on the overall efficiency of the machine. If our observations are encouraging the next stage of the work would be to produce a much larger buoy to which would be fitted rotors of a preferred design. In this way we would be able to check the performance of a model which might be about one-tenth the size of a full-scale version.
THE TRIPLATE WAVE ENERGY CONVERTER
F J M Farley, (Royal Military College of Science, Shrivenham)

This device uses the horizontal component of the wave motion. Figure 1 shows the latest version. Plates 2 and 3 are fixed together rigidly half a wavelength apart, and as a result of the resonant wave between them they do not move horizontally. Therefore the incoming wave is fully reflected by plate 2, and plates 1a, 1b, 1c, placed λ/4 in front, are at the point of maximum horizontal motion. They drive three separate pumps which can in theory absorb all the incoming power. The theoretical efficiency vs wavelength is given in Figure 2.

Note that all three front plates oscillate about a common axis (channel B), and the horizontal plate A damps down any vertical motion. Link rods C and D hold the front assembly at the correct distance from plate 2, but leave it free to heave or roll. Each plate has a separate pump so they can move completely independently.

The whole device can be of very lightweight construction. One can control the forces generated by choosing the width of the individual plates, their depth and how much they project above the water; if they project only slightly the waves pass over the top. Furthermore the force on a plate cannot be greater than the force determined by the pump pressure. As an example if the wave height is 4 m giving 160 kW/m wave energy, and each plate 10 m wide and 15 m deep, the peak force works out at 240 tonnes; but there are many other options.

Figure 3 is an efficiency curve, measured on a small model in a tank; it agrees fairly well with theory and peaks at 82%. Figure 4 is a larger model for 7 m wavelength, and Figure 5 shows the measured mooring forces, which seem to be less than the Longuet-Higgins theory.
We have tested our model (Figure 1) in natural wave conditions on a lake. The water was pumped against the air pressure in a hydraulic accumulator, Figure 6, with the output jet fed through a fixed nozzle. The position of the red float on the scale was calibrated to give the output power.

In principle both output pressure $p$ and output volume flow $Q$ should be proportional to the wave amplitude. If $Q$ is proportional to $p$ then waves of all amplitude will be automatically matched correctly. We had a nozzle of fixed diameter, ($Q \propto p^2$), but this still gives a good match over a range of wave heights. Figure 7 is a photograph of the model.

Figures 8 and 9 show the stability of the model in the Edinburgh wave tank in the large circular wave described by Mr. Salter. This is twice as large as the wave which sank the trawler on his film, and is equivalent to a 30 m high wave on the full scale.
I will now show a film of our model (Figure 1) in the lake. It is designed for wavelength 1.5 m. To go to the full scale (150 m wavelength) the output power must be scaled by a factor 10. I will quote the observed powers on the basis of full scale. You can see the freedom of the front plate to move in any direction; it is restrained in position by the water forces, not by mechanical structural forces. Here it is being launched. There it is pumping water; from the position of the float, that's just gone up to the 15 MW level. We were surprised to see the very steady jet of water we got out and you can also see the way the plates in the front are moving independently, although the whole assembly is only one wavelength wide. On the full scale it would be 150 m wide, 75 m between the two back plates, and with a spacing of about 37 m from plate 2 to the front plate — the float is now going up to the 35 MW level which is more than 200 kW/m (Figure 10). I presume this lake was a lot more rough than the Atlantic normally is to scale. We measured the wind speed; I have some shots at the end of this film where we see somewhat rougher water and the wind speed was then 12 to 15 knots.

According to Mr Russell, who has just told me about the scaling rules, if you go up by a factor of 100 in scale, you should increase the wind speed by a factor of 10 and the fetch by a factor of 100. We had a 15 knot wind with a 1 km fetch, so according to these rules the conditions correspond to a 150 knot wind with a 100 km fetch. That isn't as big as the normal fetch in the sea, but it gives you an idea of the scale conditions that we are talking about. You see the stability of the model.

Another interesting feature is that in these random waves the back two plates do not appear to move; it doesn't seem to depend on having a half-wavelength spacing. They seem not to move because the forces tend to cancel out on the front plate, they equally tend to cancel out on the back plate, and what remains tends to cancel out between the plates. So we have this rather steady 'inertial platform' on which we can mount our pumps; you can see how big waves go over the top. We are now in a rather more stormy condition, this is the 15 knot wind.

So what we have here is a very simple device and a relatively stable device; it seems to work. We still have not looked at the structural problems in the large size, although I have given an example of forces on a typical front plate and I have emphasised that you can limit the forces by the size of plates you put down, and the pump pressure that you are working to.

References


DISCUSSION

R Meir (NEL)
I would like to make some observations on Dr Evans' cylinder. I am very forcefully struck by the way that the strengths of his device and the weaknesses of the device that I was describing yesterday so very closely complement each other. You can recall me saying that one of the penalties we paid for the particular approach we adopted (using its floating inertia) was that the bandwidth of the device was much less than if we had been able to use the sea bed as an inertia reference. This device uses the sea bed, and is able to use the sea bed in deep water; this is really one of its most attractive features. You can control the maximum force in the element that is transmitting the reaction to the sea bed, controlling your power offtake; you can even imagine the device being submerged in heavy sea conditions and operating lower down in the waves. Another problem with our device is mooring resonances, but as Dr Evans said, these are obviously going to be damped out in this case. Another problem we had is power collection from lots of floating modules, which will not be a problem if the power offtake is on the sea bed, so I would strongly encourage you to keep it there. On the other hand of course the strength of our device is that we get our stiffness term for nothing: it is just the buoyancy of the water. Our power offtake is probably more easily soluble than many others. These become the big difficulties with your approach, and I don't really know how you would solve them; they are obviously very difficult engineering problems, they may even be intractable. They are problems that are really worth vigorously attacking. I hope that these remarks will encourage the Steering Committee to make sure that all the necessary effort is put into attacking them. Perhaps some members of the audience will also be stimulated to be a bit inventive about the problems, because it is inventiveness that we need.

Dr D V Evans
Could I thank you for those very kind remarks. I think you are quite right, what you gain on the roundabouts you tend to lose on the swings: the advantages which you outlined are of course compensated by a number of very difficult problems that we have got to solve. We hope we are going about it the right way; we are getting a feasibility study under way as soon as possible, with a couple of outside industrial organisations, to try and assess what a full-scale prototype would look like and see what the forces look like at full scale.

Prof D T Swift-Hook (CEGB)
Following that splendid discussion about the engineering future of these devices, it seems to me that it is even more appropriate to discuss their theoretical aspects. I found them an interesting grouping. For each of the individual devices, if it were done electrically in a transmission line or even in free space, you would call it something like a resistance or a capacitance. A static fixed cylinder is actually just a phase-change device, with no change in amplitude. The rotating cylinder is a resistance; it absorbs power fully with no phase change or transmission or anything. The other way round, as a generator, it's a negative resistance. It seems to me an interesting analogy. In electronics people take these components (resistors, capacitors and so on) and combine them together to make quite sophisticated systems. For example, a single capacitance with a single inductance tends to be rather peaky and narrow-band, which has tended to be a problem, but there are clever solutions using filter analyses to produce rather broader band widths. It seems to me that by having quite a wide variety of things to call on it may be possible to adopt these transmission line techniques to come up with more sophisticated objects. To finish up with a question, do the speakers think there is any future for devices comprised of cylinders and plates and perhaps other analytically more complicated but perhaps mechanically simpler things?

Dr D V Evans
I think there is a limit to the complexity that one wants to introduce into a new device. I think one thing that comes quite clearly out of the conference as far as I am concerned is that we really must be cost-effective in the end. Mathematically one can of course do lots of ingenious things, but the ultimate test is cost-effectiveness. As it happens, I am perfectly happy with the single cylinder. I think the electrical analogy is not entirely valid. Water behaves in its own special peculiar way; I tend to think in terms of motions of water particles and circular motions of cylinders rather than electrical analogies.

Dr G F Knott
There are already quite satisfactory mechanical analogies in terms of the damping ratios and stiffnesses, which have already been taken into account. I respect the fact that transmission line theory has a fundamentally common base to it, but I think there is sufficient information in the mechanical analogies alone to provide a basis for design. In this conference there is an evident convergence in thought as we come down to conceptual ideas; we are not thinking so much about the relationship between component parts as about conceptions. For example the raft is conceptually coming to look more like a duck, because it comes out in the mathematics; work that Brian Count of the CEGB has done on this shows the very close hydrodynamic similarity between the two concepts.
A full assessment of the impact of wave power stations on the environment and on local communities in the areas near which they would be sited will be possible only after detailed designs have been completed and specific installation sites have been chosen. However, that does not imply that we can afford to neglect these matters even at the early stages of the development programme.

A Technical Advisory Group has been carrying out a preliminary examination of the issues involved: the organisations represented on the Group are listed in Figure 1. So as to avoid dealing too much in generalities, most attention has been directed to the area of potential locations off the Outer Hebrides since many generating stations will have to be installed in that area if wave power is to make a substantial contribution to UK energy supplies (see Figure 2). The studies have shown up the general issues involved even for other areas (such as the SW and NE coasts) but of course the detailed results and conclusions will be site-specific.

Three major studies have been commissioned by the Group so far:

- an overall survey carried out by the Hydraulics Research Station, Wallingford, who acted as a focus to collect expert views on all the environmental issues
- a preliminary survey of the social and economic implications for the region by the Highlands & Islands Development Board
- an investigation of the problems of siting stations, for instance based on the Rectifier design, mounted on the seabed relatively close inshore.

I will attempt in the short time available to summarise the results and the views of the Group on these various issues.

We took a rather broad view of the meaning of the environmental impact. There can often be competition between various forms of commercial activity which depend upon different features of the same environment. Thus any effect of wave energy converters on the local population of fish may have a consequential influence on the well-being of the related fishing industry. A specific example relates to lobsters. It is possible that the installation of Rectifiers fixed to the seabed relatively close inshore could affect the local lobster population — and it is possible to think of circumstances where this might be either advantageous or disadvantageous to the lobster’s well-being. However, the wave energy converters could present increased hazards to the lobster fishing boats — and this can be regarded as a benefit to the lobsters but a possible disadvantage to the associated human commercial activities! We thought it right to include some review of these matters in our first broad Interactions of Wave Power Installations with other natural and human activities

| Interactions of Wave Power Installations with other natural and human activities |
|-----------------------------------|----------------|---------------|
|                                   | Wave power converter | Power transmission to shore | Shore installation |
| Marine ecosystems                 | *               | *                  | *                  |
| Coastal ecological, geological and physiographic features | *               | *                  | *                  |
| Navigation of ships               | *               | *                  | *                  |
| Fisheries                         | *               | *                  | *                  |
| Scenic beauty and tourism         | *               | *                  | *                  |
| Other local industries            | *               | *                  | *                  |
| Other national activities (eg defence) | *               | *                  | *                  |

The asterisks indicate the major interactions which require analysis
The influence of the converters on the wave climate is important because of the effect of the latter on the beaches along the neighbouring shoreline. Most attention was given to the western coasts of South Uist, Benbecula and North Uist. Figure 5 shows a typical beach on South Uist. These coasts are characterised by beaches of sand or shingle, which are the types most likely to be influenced by changes in the wave climate if such changes occur at all. Those in the area concerned appear to be in a state near to dynamic equilibrium, the changes from year to year in beach position, orientation, and slope being small. But the equilibrium over yearly cycles involves movement of sand in summer up the beach towards high water line, where it then dries and is blown by winds on to the dunes or 'machair' hinterland, and movement in the opposite direction in winter.

The significant but small effects of the wave energy converters on the wave climate may reduce somewhat the difference between the summer and winter beach profiles. In addition, since the steepness of the waves could be reduced if the converters were located less than 30 km offshore, there might be a net tendency for the beaches to accrete: the winter storms may well tend to cause less erosion than at present. The limited amount of accretion which might take place is likely to be a benefit because it could increase somewhat the supply of wind-blown shell sand to the machair land, thereby tending to extend the latter and increase its overall usefulness.

In summary, therefore, the effects of converters located off the particular coasts considered are more likely to be beneficial than detrimental to the beaches. The same conclusion would not necessarily be true for the effects of numbers of converters located off, say, the coasts of Cornwall or the Moray Firth. Each location will need to be considered in detail at a later stage if a serious intention emerges to locate the converters at a particular geographical site.

Possible interactions with fishery activities

The importance and size of the fishing industry in the UK renders it inevitable that one of the major considerations in the deployment of wave energy converters must be the possible effect on fisheries. The initial survey showed that the two fish to which most attention should be directed in the area west of the Outer Hebrides are herring and salmon.

In general, the areas of the UK coastal waters which are the most promising for wave power tend to overlap the areas which produce the largest catches of pelagic fish (that is, those which spend the major part of their lives in the surface or mid-water layers). The herring is the most important around the Outer Hebrides. These waters are believed to contain some of the major UK spawning grounds of the herring at the present time.

The spawning takes place on areas of clean gravel, which have not been located precisely and may indeed change from season to season. Soon after the spawn hatches, the larvae (a few mm long) rise off the sea bottom and, having virtually no propulsive power, are carried along by currents. These currents can carry the larvae around the north of Scotland into the North Sea, where they may be caught as juveniles. Finally, as the fish approach maturity they migrate back to the spawning grounds where they form the basis of an important international fishery. It is necessary to consider the interactions of a line of wave energy converters with a number of different stages in this life cycle.

It might be possible, for instance, for the converters to produce a small effect on the strength of the residual drift current. Since the larvae are spread throughout most of the water column, their transport will be unpredictable in detail.
and will be affected significantly by wind- and weather-generated currents. Whether the presence of wave energy converters could impose a noticeable overall effect on the interplay of all these natural forces is not known, but if they did then the implication would be that the larvae after a given elapsed time might find themselves a few tens of km away from the area in which they would otherwise have been, on average. Whether this matters, in terms of continuing food supply to the larvae, is also unknown — it may be either beneficial or deleterious or might indeed vary with locality.

On balance, it is believed that the effects of wave energy converters on the drift of the herring larvae will be unlikely to have a significant influence on overall survival (natural seasonal variations in the survival of herring larvae are quite large in any case, and their causes are unknown). However, further information will need to be sought before the installation of converters on a large scale on:

- the drift currents
- the behaviour of herring larvae.

The most important factor to emerge so far is that, since the herring spawn on the gravel areas of the seabed in this locality, major disturbance or removal of the gravel for construction purposes would appear to be inadvisable.

Salmon migrate over long distances in moving between their feeding grounds in the ocean and their native rivers where they spawn. Salmon stocks are an important commercial and recreational resource; the value of the Scottish salmon fishery was estimated at over £20M in 1976. The migration routes are not known in detail, but it is possible to infer that the area immediately to the west of the Outer Hebrides may intersect some of the routes.

The pattern of movement is not simple. Fish tagged at Scottish sites have been found subsequently to the north, south, east and west of the point of release. However, there is a general impression that considerable numbers of salmon may move from the feeding grounds, for instance off Greenland and the Faeroes, towards the NW coast and thence disperse to the major Scottish rivers (including those on the East coast) as well as those of Ireland and Wales.

In the locations concerned, the salmon probably swim near the surface, and the problem arises as to whether a line of wave energy devices could deflect them off course or whether the fish would simply swim through the gaps. We do not yet know enough about the salmon to be certain that they will be unaffected by a line of moving artificial objects. Moreover, the converters might create an environment favourable to large colonies of predatory birds, which would feed on the smolts, and of seals which might feed on the adult fish. The rapidly expanding colony of seals on the Monach Isles might recognise the converters as an advantageous additional habitat.

Whilst these possible interactions with the herring and salmon populations have been raised for consideration, it must be emphasized that on the balance of present evidence they are not seen as insuperable problems. An installation of wave energy converters several hundred km long could not take place in a short time but would be spread over many years. One would be able to gain experience and confidence with the early modules in good time to take corrective action if that proved to be necessary.

Floating converters well offshore are considered unlikely to have a significant effect on demersal (bottom-feeding) fish such as cod, haddock, saithe and Norway pout. Similarly, no direct effect can be foreseen on the lobster population which has increasing commercial importance off the Outer Hebrides.

Finally, I would like to stress an important logistic point. A massive installation of converters — say a line 1000 km long —
would not take place all at once. It would be spread over many years. The possible effects relating to herring and salmon which I have outlined may not occur at all – and certainly not with small numbers of converters. Dare I say that they may well turn out to be red herrings? Therefore we would be able to gain increasing experience and confidence as the commissioning programme builds up – in time to take corrective action if that turned out to be necessary.

The navigation of ships

The deployment of wave energy converters will present a hazard to shipping, exacerbated by their form – probably a very low free board which will render them relatively invisible to ships either by sight or by radar under most sea states.

Except for the English Channel, detailed information on the pattern of shipping movements around the UK coasts is sparse. However, off the Outer Hebrides the present shipping movements are mainly concerned with the fisheries. Apart from the necessity to consider the influence of the deployment of arrays of converters on fishing operations generally, the hazards to fishing vessels can be of two kinds:

- collision
- the formation of rougher seas, of particular importance to smaller boats.

It will be necessary to mark the positions of the converters with warning lights and radar reflectors. This will not be a trivial problem, since the markers may need to be sited at a greater distance above sea-level than the structure of the converters and will need to be relatively stable in the horizontal plane. Gaps in the line of converters, perhaps 2 km wide, would probably have to be left as navigation channels for fishing vessels and could well have to be marked to a higher standard than the converters themselves. The requirements may turn out to be quite complex, but no new matters of principle appear to be involved and the matter will be considered by the appropriate responsible Authorities as the occasion demands.

The hazards to small boats of rougher seas arise from the fact that part of the wave spectrum will be reflected by the converters. The reflected waves will combine in front of the converters with the incident waves to produce a complex pattern in which there will be increased wave heights, standing waves and an increased incidence of breaking waves. This pattern could be quite hazardous to small boats. However, it is possible that this effect will be confined to a distance close to the converters and the declaration for other purposes of an exclusion area around the converters may be sufficient to cover this point. Moreover, there would be a counterbalancing advantage from the fisheries point of view of calmer water behind the converters, though the exclusion area may have to cover this too.

A new feature of the Outer Hebrides area which may emerge is the possible designation of clearways for the passage of deep draught oil tankers to and from the Sullom Voe terminal in the Shetland Isles. One of the clearways could pass between the Flannan Isles and the Isle of Lewis and the possible interactions with the precise location of some of the converters (especially off Lewis) would have to be resolved.

Preliminary information from other potential wave energy locations has not revealed any additional matters of principle but has indicated that problems concerning the navigation of shipping would be much more complex than those in the Hebrides area. For instance, some possible locations off the Scilly Isles may intersect international waterways which could not be altered without international agreement, and if the converters were within 20 km of the southern Cornish coast careful analysis of the interaction with the important mackerel fisheries interests would be required.

There may be a possible line for converters across the Moray Firth, as in Figure 6. The complex nature of the potential interactions with fisheries operations is obvious from the Figure. These may be compounded by future exploration and production activities associated with offshore oil and gas.

Economic and social development of local communities

As with the environmental issues, first attention in the preliminary review has been given to the Outer Hebrides area. The latter has no large-scale industries and is characterised by a declining population and relatively high unemployment. The Western Isles Island Council has stated that its primary objective is the reversal of the trend of population decline due to the persistent selective out-migration from the area, and the improvement in the situation of the population in terms of employment. Installation on a large scale of wave energy converters could assist the attainment of this objective in two ways:

- the labour force needed to operate and maintain the
system
- the possibility of utilising some of the power to establish new industries in the area.

Whilst the prospects for setting up major industrial developments in a remote and difficult area with a sparse population may appear daunting, there are a number of examples where this has been achieved successfully, for example the Dounreay Nuclear Establishment, the Uist Rocket Range, the Kiahorn construction site, Sullom Voe oil terminal, and oil-related development on Flotta. Whilst introducing the industrial infrastructure associated with wave energy would be a formidable task, the evidence from these earlier activities indicates that the difficulties would be by no means insuperable. The HIDB study also indicated that the availability of land suitable for such development should not be a constraint.

Construction of the converters may well take place elsewhere because of the very high tonnage involved, the converters then being towed on to station. However, a small fleet of tugs and supply boats would be required which could be based locally. Whilst the main ports in the Outer Hebrides have developed historically on the eastern coast (i.e. looking away from the Atlantic), and the passages between the Isles virtually all present difficulties, there are some suitable locations on the western coasts.

The inspection and maintenance of moorings for the converters will be vital - the converters cannot be allowed to break adrift - and a small workforce of skilled divers would be needed, although probably less than for the offshore oil industry in the North Sea.

A much larger requirement than the supply bases for equipment and skilled manpower could arise from the need for one or more maintenance bases. There is likely to be a variety of maintenance and repair work which cannot be carried out at sea and will require the converters to be towed to deep well-sheltered water with possible dry-docking. Criteria for such sites would include:
- shelter from sea and swell
- adequate depth of water
- entrances and configurations suitable for manoeuvring the unusual shapes of the converters
- land at the shore physically suitable for development
- road access or the capability of road access
- minimum practicable towing distance from the sea stations.

It is difficult to identify any particular sea loch which would meet all these criteria. The labour force required to operate a maintenance base for a large array of converter stations might run into thousands of men rather than hundreds, much of it highly skilled. Until both the design of the converters and the logistics of the whole system have been developed much further, it is not possible to be more precise about the requirements for such shore-based facilities and manpower.

It is unlikely that the converters themselves will be visible from the nearest shore, unless they are of the type fixed to the seabed and located close inshore and even then they would not be likely to rise above the horizon, but one of the most important aspects from the visual amenity point of view will be the method and route by which the energy from the converters is carried to the mainland. However, the problem cannot be analysed in detail until several related decisions have been clarified. In particular, decisions between electricity and energy-intensive chemicals as the desired output from the system, and between local use of electricity for new industries or feeding to the national grid (see Figure 7).

The most difficult of the visual amenity problems is likely to arise from the fact that a system consisting of a large array of converters feeding electricity into the national grid is unlikely to

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Figure 7
be able to avoid transmission across Skye. Very detailed and careful transmission route planning will be needed.

Converters fixed to the seabed

Most of the aspects I have described relate to floating arrays of converters at least 10 km from the shore. Converters mounted directly on the seabed and closer inshore will involve different considerations. They appear more likely to give rise to significant environmental consequences during installation and operation, and could represent a permanent and possibly undesirable change to the environment unless some technically and economically acceptable method for their removal at the end of their service life can be devised.

On present designs the converters are very large and would require massive quantities of constructional materials. Whilst construction may take place elsewhere, with subsequent floating into position, the seabed-mounted converters could also require additional large quantities of material for the preparation of the seabed which might well involve extensive local quarrying. The magnitude of this potential problem will not be known until further civil engineering studies of seabed-mounted devices have been made.

As a first step, Rendel, Palmer & Tritton produced a report for us on the seabed conditions off the Outer Hebrides, between about the 15 and 25 m depth contours. One of the most interesting features to come out of that was that the environment may be able to hit back at the converters! Figure 8 shows the areas of interest off the western coasts of Benbecula and North and South Uist, where there are dense forests of the seaweed Laminaria hyperborea. This can grow to a height exceeding 2 m and the stipes, which are tough and fibrous, can achieve a diameter in excess of 8 cm. The fronds can be of similar height and are cast annually. Figure 9 is an underwater photograph of this weed. Fouling of the seabed-mounted devices by such material could be serious: extra costs may be incurred by the need to install anti-fouling devices or to construct the converters beyond the 25 m depth contour.

The possible effects of the installation and operation of seabed-mounted converters on the inshore marine ecosystem off the Outer Hebrides have received preliminary review by the Scottish Marine Biological Association. Some changes may well occur: for instance alteration in the circulation pattern of water and the more sheltered environment behind the converters might lower the growth of Laminaria hyperborea and the amount cast annually on the Hebridean beaches. Conditions may be created also around the converters which favour the growth of Laminaria scharina instead of the Laminaria hyperborea. This may again have technical consequences for the converters themselves since Laminaria scharina can transport attached stones of substantial size during storm conditions – creating a different type of fouling problem.

The waters west of the Outer Hebrides form one of the most important lobster fisheries at present in the United Kingdom. There might be some effect on the behaviour and population of the lobster which would be dependent on the exact location and spacing of the converters.

Converters mounted on the seabed closer inshore will have more significant consequences which will require detailed examination if a decision is made to build them on a large scale and when the sites have been identified.

Conclusion

In conclusion, I would summarise by saying that our studies...
John Moore – a profile

Mr John Moore, Parliamentary Under Secretary, has particular responsibility for the coal industry, energy conservation and research and development, including all work on renewable energy sources. Mr Moore has been the Member of Parliament for Croydon Central since 1974. He is an economics graduate from the London School of Economics, where he was President of the Students Union in 1959-60, and comes to the Department of Energy from a career in finance during which he spent some five years with institutions in Chicago. Before entering Parliament he was a Conservative Councillor in the London Borough of Merton.

Mr Moore is keenly interested in all aspects of energy research and development. One of his first requests to his scientific staff was the preparation of an itinerary of visits to research establishments and project sites which would enable him to gain first hand knowledge of current energy research and development work and provide opportunities for him to question those engaged in the programmes about likely profitable lines of future development. On the coal front, in addition to a comprehensive programme of visits to pits throughout the country, Mr Moore has been to the Coal Board’s Coal Research Establishment at Stoke Orchard where he saw, in particular, the important work being carried out there in making oil from coal. In September Mr Moore also visited the United States to see the 250 ton/day Exxon Donor Solvent pilot plant at Baytown, Texas and the 250 ton/day H-Coal pilot plant at Catlettsburg, Kentucky. He visited Harwell with the Department’s Chief Scientist, Sir Hermann Bondi, early in the summer for discussions with ETSU staff on progress with the renewable energy and energy conservation programmes. The Minister plans during the next 12 months to make a series of visits to renewable energy projects. In August he met members of the Severn Barrage Committee and accompanied them on a visit to the Severn Estuary to examine proposed possible sites for a Severn tidal barrage. He intends to visit the French tidal scheme at La Rance in the near future. In November he will be going to see the drilling rig in operation at Marchwood near Southampton where the Department of Energy is drilling its first exploratory geothermal borehole, the project described in this issue’s leading article.

Among the other engagements which Mr Moore has undertaken during his first few months in office are the inaugural meeting of the Energy Group of the South London Consortium, a local authority organization noted for its excellent work in insulation and controlled ventilation for buildings and which was also responsible for the design of the Whateley Road solar heating scheme in Southwark, and a television appearance on the BBC’s programme ‘Brass Tacks’ where he outlined the Government’s stance on energy conservation and renewable energy sources.

Mr Moore sees the economic development of new forms and sources of energy as an exciting challenge both to technologists and politicians. He has made it clear in public statements that the Government regards as important the continuance of research and development into renewable energy sources and that appropriate Government funds will be allocated to this work.

International collaboration on wave energy

The sea-going vessel Kaimei off the coast of Japan to test air-turbine generators which are driven by air displaced by the action of waves. As reported in the previous issue of RE News, the UK designed and built one of the generators as part of an IEA joint programme between Canada, Eire, Japan, UK, and USA. Latest reports indicate that the UK generator is working well and data are being collected.

Compiled by the Energy Technology Support Unit, Harwell.
Energy storage — a new study

Storage, an especially important area of investigation for renewable energy sources, is the subject of a recently initiated review being carried out at ETSU. The aim of this work is to identify any gaps in energy storage technology and to determine whether existing lines of investigation can develop the technology in a timescale appropriate to national needs. The study is being done in collaboration with the Science Research Council which is paying particular attention to areas of work that might be carried out in the universities.

The development of the use of renewable energy could be strongly influenced by available storage. For example, the success of solar heat as an energy source in the UK will depend heavily on being able to provide a system to meet the mismatch between supply and demand — short-term storage over a period of a few days to supply heat at night or on cloudy days, and long-term storage to provide heat during the winter when sunshine is available least. Technologies depending on reversible chemical reactions and on latent heat could be of particular interest here.

Other renewable energy sources like wind and waves would be expected to generate electricity for the central distribution system. Here storage could be thought of as a problem of the total system. If, however, renewable sources were to represent a large fraction of the supply or if, as is quite likely, they were connected to the central distribution system by a long spur line, then directly associated storage may be necessary. Pumped water storage is used now in the electricity generating industry, and other high-capacity centralized storage techniques at the generating unit and in the distribution system are already being assessed by the electricity industry.

The review will also cover applications of storage technologies in energy conservation.

For further details contact (ETSU) Dr Ken Linares, Building 552, AERE Harwell, Oxon. [Telephone: Abingdon (0235) 24141, extension 4628] and (SRC) Dr Mike Russell, Rutherford Laboratory, Chilton, Oxon. [Telephone: Abingdon (0235) 21900, extension 6232].

Recent reports

A number of recent reports arising from work carried out for ETSU in the Department of Energy’s renewable energy programmes are detailed below.

Catalogue of geothermal data for the land area of the United Kingdom
A J Burley and W M Edmunds

A catalogue of data relevant to the geothermal prospects for the UK compiled from borehole records etc., at the Institute of Geological Sciences (IGS) in London. It includes information on microfiche about the location of boreholes, temperature heat flow and, where appropriate, geochronological properties of the water present. Another section includes tectonic, data location, and chemical geothermometer maps. The main text of the catalogue gives background information and some interpretation of the results. The first volume records data available up to June 1977. Supplements will be published as necessary to update maps and data.

The catalogue costs £10 and is available from the Librarian, Department of Energy, Thames House South, Millbank, London SW1P 4QJ.

Development of large wind turbine generators. A design feasibility and cost study

The report summarizes a one-year design feasibility and cost study on large wind turbine generators suitable for network connection. The study was carried out by a consortium of companies and forms part of the Department of Energy’s wind energy programme. The possible design of a suitable machine, economics of installation in sample areas, and the likely environmental impact are all considered. A detailed design study has now been initiated as a continuation of this work.

The report is available free of charge from the Librarian, Department of Energy, Thames House South, Millbank, London SW1P 4QJ.

Environmental impact of renewable energy sources
This report was prepared by ETSU and presented to the Commission on Energy and the Environment in January 1979. It reviews the various issues concerning the possible environmental effects of obtaining energy from renewable sources in the UK.

The report is available free of charge from the Librarian, Department of Energy, Thames House South, Millbank, London SW1P 4QJ.

Students benefit from solar heated water

This student’s hostel at Kirkcaldy, Fife, employs 72m² of solar collector installed on its circular roof to heat domestic water for the hostel. The absorber panels were developed by Tube Investments Ltd with partial funding from the Department of Energy and use a novel manufacturing process in which superplastic aluminium is formed around stainless-steel water tubes on a single machine. This enables small quantities of specific designs to be manufactured economically. The hostel is to be opened officially in November and the Department is jointly supporting a two-year monitoring programme to determine the operating performance and reliability of the panels and system as a whole.

Further information: Mr D W Jefferson-Loveday, ETSU, extension 203.
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(T__) : Sharing twin bedroom
(N) : Non-resident

- 4 -
1979 WAVE ENERGY PROJECTS REVIEW WORKSHOP - PROGRAMME

Sunday 16 December

4.30 - 6.00 Participants arrive (by 6 pm). The first of three opportunities for the general informal interaction that people say there is not enough of.

7.30 - 9.30 Introduction (Dr F J P Clarke). Report on past and future programme, and presentation of some questions of overall strategy (C O J Grove-Palmer). The situation as now seen by WESC and programme management. By the end of the workshop progress so far will have been debated at length; the strategy questions raised at this stage will provide part of the agenda for later syndicate meetings.

Monday 17 December

8.30 - 10.20 Device team presentations. Each team describes its progress to date (towards the target estimated cost of £0p/kWh). In this session:
NEL (35 min) QUB (15 min) Vickers (15 min) HRS (10 min) Lancaster (35 min)

10.50 - 1.00 Device team presentations. In this session:
WPL (35 min) SEA (15 min) RMCS (15 min) Bristol (30 min) Edinburgh (35 min)

2.00 - 3.45 Syndicate discussion sessions. Each syndicate has 10 members. In this session, each syndicate will deal with a strategy question (as posed on the previous evening) and discuss the presentation of one of the 10 devices (at least one member of that device team present).

4.15 - 6.00 TAG Chairmen's presentations. 6 chairmen (or their nominees) describe their TAGs' progress to date (towards the Department of Energy objective of a fully-researched technology).

7.30 - 9.00 Informal interaction. The second such session; there will be a cash bar, and no formal programme. These informal sessions will provide parallel opportunities for some more specialised presenters to discuss their topics with those who are interested; details of presenters and subjects will be advertised at the beginning of the workshop.

Tuesday 18 December

8.30 - 10.30 Syndicate discussion sessions. Each syndicate continues its discussions from the previous day, but with an additional topic of one of the TAG presentations (at least one member of the relevant TAG present).

11.00 - 1.00 Reporting session. Each syndicate reports its discussions, making full use of visual aids (overhead projector slides, flipcharts etc) to increase impact and digestibility.

2.00 - 3.00 Informal interaction. The last such session with no formal programme. It gives another opportunity for parallel discussions, or an additional plenary session if one is needed.

3.00 - 4.30 Final session. Summary of workshop discussions, and discussion of final report. Programme management's response to the reports given earlier by syndicates. It will not be possible to issue a written final report at this stage, but it will at least be clear by now what its contents should be.

ETSU
30 November 1979
so far have not identified any major deleterious environmental effect of large numbers of floating converters located off the Outer Hebrides, but more detailed information will be required eventually on aspects relating to the herring and salmon fisheries to confirm that they will not be affected significantly.

The preliminary work has shown that not only are studies of environmental matters important in their own right, they may also have an important feedback into the choice of design features of the converters.

DISCUSSION

Dr P K Probert (Nature Conservancy Council)
I'd like to make one or two points about Dr Dawson's valuable review of the environmental and social implications. You talked about accretion of sediment on the beaches of the Uists and Benbecula. I wonder whether sediment might accrete on the sheltered side of seabed-mounted devices, and whether it is likely to be considered a problem; it might smother rocky grounds that were valuable for lobster fisheries. I am also pleased that you brought up the question of the ultimate fate of seabed-mounted devices. Leaving them permanently in situ would not necessarily be a problem, but it would certainly bring about a number of changes in the inshore area; one might envisage a line of artificial leaps, and possibly commercial species of fish have been known to be attracted to artificially-constructed reefs. You didn't touch on one important aspect of fisheries: the economics of some pelagic fisheries off the Outer Hebrides depend on the length of the round trip. If the vessels have to go considerably out of their way to find a gap between converters, it could make that fishery uneconomic; I am thinking particularly of a blue whiting fishery there. The possible indirect effects of wave energy converters could be more important than direct effects on the marine environment. There will be a temptation for industries which are attracted to the Outer Hebrides by a ready supply of offshore power to use the machair strip of flat agricultural land along the Atlantic coast of the Uists and Benbecula. If possible industry should be steered away from the machair; it is valuable agricultural land of some nature conservation interest. One minor point on social implications: I wonder if the guided missile range on South Uist, which does employ a considerable number of people, is compatible with a line of wave energy converters.

Dr J K Dawson
To deal with the last point first, it's not necessarily compatible, but I don't know whether the rocket range is going to be there in 20 years' time. We certainly know about it and take note of it, but it is not a worry to us at the moment; there are plenty of other places where converters can be deployed without putting them off South Uist first of all. Most of the points you made were comments rather than questions, and I agree with them. Accretion of sand behind fixed converters could well happen. We haven't examined it in detail yet; we know that the lobsters might be affected, but I did say in my talk that the effects on lobsters might be advantageous or deleterious - we don't really know yet.

Prof D T Swift-Hook (CEGB)
Your paper brings out the contrasts between environmental considerations and economic ones, which are very important. Clearly environmental factors are going to dominate - people being put out of work is a very emotive thing, and the fishing industry is very important. Of course the annual value of a strip of wave energy devices along the islands would pay for the entire UK fishing industry, of which the island fishing industry is a minute part. The few thousand jobs that you mentioned in the possible shore base have a hundredth of the value that would accrue from the wave power you are producing (and I mean the value of wave power, not its cost which you remember is about 20 times its actual value). So you are balancing things which are not equal economically - the value of the wave power far outweighs the economic value of all these environmental considerations. Nevertheless, everybody is perfectly clear that environmental considerations are going to dominate. Perhaps the fact that the economics of paying for environmental things are adrift by a factor of 10 or 20 but don't stop us doing them, should give us some comfort when it comes to worrying about the economics of wave power itself. If I might ask a question, having made that comment, what do you think is the comparison between the first megawatt and a whole thousand megawatts? Economically a thousand megawatts is worth a thousand times the first megawatt - what about environmentally? You might find it just as easy to install a thousand megawatts as one.

Dr J K Dawson
'Ve don't know until we try' I think is the answer.

R M Gove (SSEB)
I mentioned this morning the wayleaving of overhead lines, and I think the point is worth repeating. Dr Dawson referred to the need to put a transmission line across Skye, but I would point out that environmental problems with the lines are only just beginning when you cross Skye. Of 2000 MW of power generated, some 200 MW might well find its way into the Scottish system, but the other 1800 MW has to go right down into the English network; it would be quite wrong to imagine that the problems are local and merely a matter of crossing Skye.

Dr J K Dawson
I agree with that. I would comment, though, that strengthening the line down to Manchester doesn't actually raise any new points of principle, whereas what we were looking for in these early studies were new things specific to wave energy in this particular location. The transmission lines from north to south may have to be strengthened anyway, whether we have wave power or not. There is nothing new in that, so we haven't paid much attention to it so far.

R C H Russell (HRS)
I wanted to give a slightly different answer from the one that Keith Dawson gave on the building-up and erosion of beaches. The usual picture is that long low waves build up beaches, and short steep ones drag them down. Floating wave energy converters will probably leave alone the long wave component which will be somewhat reduced in height; the spectrum of the waves arriving at the coast will be much more concentrated towards long low waves, and the beaches will probably build up. Until this meeting I thought that was an advantage. With a line of rectifiers off shore, the waves will be very largely inhibited except where there are gaps; the wave arriving at the coast will be the locally-generated one which will be short and steep, and there may well be some erosion.

S H Salter (Edinburgh University)
There are 27 aids to navigation on the inside of the Hebrides, and there is one on the outside of the Hebrides. Are the Hebrides considered as a hazard to shipping?

Dr J K Dawson
It's like the salmon: we don't really know for sure!

M J Platts (Wavepower Ltd)
I would like to query how much wave energy we might in the end be trying to deliver back to present centres of occupation.
We've tended so far to think in terms of creating a community up there of a few thousand people working on wave power station maintenance and possible industrial uses. But think of any community that you know, and of how many people in that community work in a basic supply industry; we have to think in terms not of a few thousand people but of tens of thousands of people up there, forming a community in their own right, and self-stable. Then perhaps only the last trickle of energy is exported back to the mainland.

Dr J K Dawson
I think that's in line with the picture I was trying to put over. Although we talk about bringing all the power down to the centre of England, it will be a very long time before we are able to do that. The community that builds up naturally in the Outer Hebrides, for instance, could itself demand more power; I wonder if we ever get out of that vicious circle.
In his opening address to this Conference the Minister, Mr Alex Eadie, talked of the severe technical challenge of wave energy. When Dr Clarke made his introduction to the presentations you have heard, he told you that the programme had reached a stage where problems loomed larger than solutions, and both speakers expressed their confidence that the UK Wave Energy team could lick the problems.

However, in my position as Programme Manager, I am much closer to the people who make up that team, and I can tell you that this unique group of people thrive on challenge and problems. It is meat and drink to them. I am confident that given the right strain of onions they won't just lick the problems they will eat them.

There have been some suggestions that the cost analysis which we briefed RPT to carry out was in the nature of a hatchet job. In a way there is a small element of truth in that, because there is nothing quite like the thought of an execution to concentrate the mind. The real purpose of the exercise however was to help us identify the problem areas on which we have to concentrate.

If we were to take the costs too literally in terms of thousands of pounds and pence per kilowatt-hour we would mislead ourselves. I can remember over a year ago suggesting that we should express these costs in some meaningless form of currency like European units of account. The costing exercise does emphasise in a sharp and perhaps abrasive way the high-cost centres on which we must concentrate.

In addition to cost reduction however the most important aspects of the work in the coming year are:

- sounder wave data
- credible power take-off from the mechanical devices like ducks and rafts
- spine articulation
- behaviour of oscillating water columns in real sea
- examining the Lancaster flexible bag to see if it lives up to its initial promise
- mooring
- seeking a new concept which can overcome the size and survival problems of the first generation of devices.

I want to give you an idea of my own personal views of what should be done.

Wave Data – Mariners, oceanographers and naval architects have for generations been collecting data about the height of waves. But for wave power we need more than the height of waves; we need to know a great deal about the direction from which they come. To get this directional data we need to develop new measuring instruments and new analytical methods. You saw this morning what a complex subject this is, but work has been started and it should expand.

Power Take-off – You have seen some of the power take-off ideas being suggested by Wavepower Limited and Stephen Salter. We should be mounting a hard critical engineering examination of these ideas and also initiating innovative studies to try to produce credible engineering solutions, if they are at all possible.

Spine Articulation – You have seen how Sir Christopher Cockerell’s team at Wavepower Limited are beginning to think of rafts operating from a common back section, and how Bob Meir at NEL is examining the idea of longer strings of oscillating water columns. These designs have much to gain from a study of spine behaviour which was first started by Stephen Salter’s team working on ducks; a splendid example of the way the once disparate teams are forming into a corporate whole. We should be studying these spine problems.

OWCs in Real Sea – You have heard about the advantages of the air turbine in the oscillating water column. Because of these, I believe it is essential that the NEL team get real sea experience by operating their device at about 1/10th scale in the sea off the south west coast of the Clyde. They should of course also continue their more fundamental studies of the device configuration at the small scale in the Edinburgh University tank and their studies of the 1/10th scale turbine which Bob Meir spoke about.

The LFB – The new device which Michael French described has very promising features – notably a low cost structure and a closed air circuit. The basic feasibility however has still to be proved. We should therefore be examining it very thoroughly, and subjecting it to wide tank tests – perhaps in the new wide tank which we hope will shortly be built at the Wavepower Limited site near Southampton.

Mooring – You will have noted the problems of using existing mooring equipment for wave power devices which Roger Hancock talked about this morning. We should be mounting an intensive study in this area probably by having some large object out in the real blue sea. Roger’s group are already considering this.

New Concepts – Above all we should be very actively seeking a radical new approach to the wave energy converter which will enable us to reduce the cost of wave power in the same way that NASA was able to reduce the cost of air travel below the $30,000 per mile which the Wright Brothers first estimated.

Finally let me say that I have only highlighted the most important areas of the work. The other parts of the
programme which are already started should of course continue until they have made their full contribution to our understanding of this important new technology.

DISCUSSION

Dr N W Bellamy (SEA/Lanchester Polytechnic, Coventry)

It seems that it is not just a device problem that we shall have in the future, but a system problem. One technology very often depends on another. We can replace a lot of problems by the solution of one and that's the energy farming system; energy farming depends on storage on a device structure. Energy farming increases the size of resource tremendously; we don't have to draw lines down the Hebrides (which I think is probably one of the worst possible locations in the world at the moment). The device should be able to follow the optimal wave energy line that it needs. It can avoid the calm areas, it can avoid the survival areas, and it can optimize its energy input by a significant amount. It also avoids the problem of spacing between devices, as there is plenty of room in the Atlantic. RPT's directionality problem disappears; so do the mooring problem (which on its own can kill a device) and the transmission costs. So, all in all, we reduce a lot of problems down to one -- which unfortunately is the biggest one. What I would like to see is a wave buoy that moves around at 5 knots under computer control, maximising the energy by wandering around the Atlantic. I'd bet the energy input to that buoy would be a much better characteristic than the wave buoys off Uist.

C O J Grove-Palmer

It's a fascinating idea. I once drew lines on a Mercator projection of the world, at 50-mile intervals all the way across the Roaring Forties in both the northern and the southern hemispheres; I worked out that we could increase the size of the resource by 7 orders of magnitude, and I thought that was great. But it doesn't just reduce to one problem. You're suffering from the new device syndrome: the problems you get look easy because you don't know what they are. I think it's a nice idea, but it's not for this generation.

D Ross (Journalist)

But surely the idea of putting buoys out to sea and seeing what happens is precisely what the Japanese have done. They have pushed out the boat to see what happens, instead of feeding everything into computers and into committees and eternally waiting for something to happen.

C O J Grove-Palmer

David, if you think we have just been waiting for something to happen for the last two years, you haven't been listening. We certainly aren't waiting. There is a difference of approach between the way we are doing it and the way the Japanese are doing it, I agree. We have a good collaborative agreement with the Japanese and a lot of useful information is exchanged; we are very pleased to have Commander Masuda and Mr Odani here at this conference and they will be coming down to talk to us tomorrow. We do not in any sense think that they have upstaged us. We are all in the business of finding out how to do it, and the more different ways we have of doing it, the more likely we are to succeed.

Dr D McLlhagger (Queen's University, Belfast)

Two of the major problems that have been mentioned at this conference have been mooring and transmitting the power to shore. I wonder how many people have thought of driving ships by wave energy. You do not need to moor the vessel and you might be able to include self-rectifying turbines. Although an ancillary engine would be required just as it may be in a wind-driven vessel, the power here is very much more concentrated. So I wonder if we are missing out on a very big opportunity in cheap transport.

C O J Grove-Palmer

I am not sure the shipping industry would agree with you that waves present a big opportunity; but I can tell you that some time ago Professor Michael Longuet-Higgins produced at a Royal Society meeting a little boat which was driven by a Saltier duck. The idea has been kicked around, but our programme is essentially aimed at generating energy for the UK and we haven't actually considered it.

Dr N Hogben (National Maritime Institute, Feltham)

The possibility of using wave energy for ship propulsion is an interesting idea, but is likely to involve difficulties in maintaining operating schedules with sufficient reliability. Personally I believe that since wave energy derives from wind energy there may be more promise in ships which make more direct use of wind power. Perhaps serious consideration should be given to greater use of sailing ships.

R M Gove (SSEB)

Mr MacGregor raised yesterday a question about security which I thought was rather lightly dismissed. There is no doubt at all that the question of security comes into this. I am sure I speak both for the CEGB and the SSEB in saying that the supply industry would be far more interested in 2000 MW of plant on dry land than bobbing about in the North Atlantic. I think any appraisal of the value of wave power would need to take account of that.

Dr J K Wright (CEGB)

I think it comes down to the basic philosophy of why we are thinking about wave power. Dr Clarke has explained the insurance nature of wave power research. If it is a case that we can't for some reason (and I wouldn't understand this reason) have nuclear power, if it is a case that miners won't dig coal out, and we are looking for something else, then from an insurance point of view we would be very anxious to see wave power. In a situation where we have a lot of options we have to choose the best one; if there are such improvements in wave power (and I honestly hope that there will be) that it is competing with the other sources of power, then there is clearly a very large market for it and the disadvantages of it being out to sea could conceivably be offset. But as Sir Hermann said last night, it is going to have to compete in the market place on its own merits.

Dr F J M Farley (RMCS, Shrivenham)

Could I say a word about the scaling of these things? We all know that the power scales as length to the power 3⅔. If we scale up our apparatus in proportion keeping all dimensions the same, the mass increases as length cubed. But we know also that in going from the mouse to the elephant the result will be too weak. Ideally we should increase the thickness of the members by another factor of length, so that the mass increases as length to the fourth. Probably by being clever it would be somewhere between length cubed and length to the fourth, not far away from length to the 3½. In other words, in going to the big scale we are not likely to increase the kilowatts output per mass of equipment. So why not start small? A smaller scale will be easier to make and probably will not increase the cost per kilowatt.

C O J Grove-Palmer

To some extent of course we are starting small; we have got what Norman Bellamy has referred to as the odd megawatt-hour being generated in Loch Ness. There are small devices about, and maybe they could be cost-effective, but I rather doubt it.
Dr N W Bellamy
If you scale the Loch Ness model up to full size as it is, it sinks. When the members are thickened up, it meets the buoyancy restriction.

I Glendenning (CEGB)
As transmission is apparently much cheaper and easier on the fuel. Now for wave-generated electricity at Perth we are dismissed it with some scorn on the basis that when you land week yet.

Dr D Mollison (Heriot-Watt University)
I want to comment on this smaller device size, and what I think of as the Aberdeen delusion, which has been raised several times — the idea that there is a large scaled-down climate off the north-east of Scotland. I think that we shall in fact find that the power there is lower, not because of scaling-down, but because there are more calm periods there. I should add that we are putting a Waverider buoy there to help us find out; and it might be a good place for a first full-scale trial because it is handy for the electrical grid. But the advantage of the west coast side is that it has a lot of swell, so that power is firmer throughout the year. To come back to the smaller device size, the reference design for ducks was based on the old OWS India data. When we saw the South Uist data and started doing calculations with it, we realised that buck diameter would come down from 15 m to 10 m, and might go further. The future may be for smaller devices, but staying on the west coast side.

Prof D T Swift-Hook (CEGB)
I wanted to address this question of availability and perhaps try and quantify it a bit. The sort of availability that we are talking about for wave power might (if it was a very highly rated device) be in the region of 30% load factor. Clearly nobody is aiming for a very high load factor, and it is accepted that there will be significant periods when no power is generated. When we talk about availability on a conventional power system, and install 100% standby capacity on transmission plant, we're aiming at something like 99.98% availability; if we omitted the standby capacity, availability would drop dramatically to 99.9% or even perhaps only 99%. The important thing is that the outages we can expect due to unreliability of plant are an order of magnitude (or maybe more) adrift from the outages we should expect anyway from the randomness of the waves. It seems to me that we should keep the two separate in our minds. The lack of reliability is only going to matter when we are aiming at very much higher levels of availability. What we shall have to do with wave power, and indeed any of the variable sources, is take care of it some other way. Storage is sometimes suggested, and another option is to have standby capacity, perhaps from gas turbines.

J M P Soper (Sea Energy Associates Ltd)
Could we perhaps just discuss this hydrogen route once more? RPT in fact suggested in their report that the hydrogen route should at least be re-examined; Ian Glendenning has dismissed it with some scorn on the basis that when you land it it is like to cost something like 4 times the price of fossil fuel. Now for wave-generated electricity at Perth we are talking about something like 10 or 20 times the present cost of electricity generation; to me a figure of 4 times the cost of fossil fuel is the most encouraging figure we have had this week yet.

I Glendenning
You are not comparing like with like. If we are talking about energy landed at the prices that have been discussed at this conference, hydrogen is not 4 times but probably 50 or more times the cost of fossil fuels. I am afraid the relativity will remain constant. Within TAG 6 we have been in the cosy position of being able to deal with things in relative terms, and not absolutely.

A C J Baker (Binnie & Partners)
I am a civil engineer; I have been engaged for some years in water supply. In pipeline design the change of internal roughness with time is of fundamental importance and laboratory tests have been used to establish how flow characteristics change with roughness. We have see today very exciting models of oscillating cylinders and so forth, all of which are patently superbly finished and superbly smooth. Earlier today, the possible rate of development of marine growth on structures in the sea was defined. It seems to me that laboratory tests could establish how efficiency loss could be related with the roughness of marine growth. Some of the wave energy converters are obviously more susceptible to marine growth than others, and some types of movement of wave energy converters may favour growth more. We have also heard mentioned today the question of anti-fouling. I have limited experience in this, but anti-fouling essentially relies on poisoning the marine organisms that wish to live on a surface; it deteriorates with time, and needs replacement. Dr Dawson in his paper didn't mention whether very large areas of marine anti-fouling applied regularly in a particular environment would have any adverse effect on, for example, the Hebridean lobsters.

M J Platts (Wavepower Ltd)
I think that we have one of the devices which is perhaps less susceptible, externally at least, to fouling. We have a lot of spare buoyancy, and also we have a very high added mass — there is a lot of water that moves with the raft — so external fouling doesn't really bother us hydrodynamically. Perhaps it affects corrosion, because there is more corrosion under fouling, so we might be wanting to use anti-fouling paints externally. Internally, we are looking at the moment at low pressure sea water pumps and turbines and ducts, and we will be very interested in anti-fouling paints internally because of the duct efficiencies.

Dr J K Dawson (ETSU)
We recognise there may be a problem, if we want to use large quantities of anti-fouling material, as to the effect it might have on things that we don't want to affect. We haven't looked at it in detail yet — it's a problem for the future.

R Meir (NEL)
The questioner might well have had oscillating water columns in mind when he was making this point. While I don't want to underestimate the problem of fouling, it's nice to be able to point out that on this occasion the square-cube law is on our side, because it is really the surface area that is doing the harm here.

Dr J A Hudson (AERE Harwell)
To answer the question about fouling on internal water mains, I think the CEGB experience with chlorinators is excellent here and I foresee no problems at all.

Dr N Hogben (National Maritime Institute, Feltham)
I wish to comment on the list of major problems with which Mr Grove-Palmer introduced this session. If this is a blueprint for determining future priorities I feel it should be more explicit in identifying what seem to me to be still the two most
There are some important differences in the objectives which influence structure design. Most North Sea platforms are designed to minimise the incidence of wave loads, and in many cases the dominant structural members are vertical circular cylinders. Wave energy devices on the other hand must be designed to capture as much wave energy as possible, which may be expected to promote a greater exposure of hardware to wave forces. In practice there is a great deal of common ground; I believe that much can be learned from offshore experience in the North Sea. Considering the very wide range of types of structure involved in North Sea operations, it would be surprising if there were not a considerable overlap with the equally wide range of types of wave energy device being developed. This is amply confirmed by the extent to which analytical techniques for loading and dynamic response prediction used for the design of North Sea structures can be adapted for application to wave energy devices. A number of devices involve circular cylinders to which methods based on the use of Morison's equation, a standard tool of the offshore industry, should apply. Many others involving more complex structures have been shown, as Dr Smith reported, to be amenable to analysis by the adaption of methods based on diffraction theory already extensively used for design of North Sea structures. It must be recognised moreover that wave energy devices, though primarily concerned with capturing wave power, must be designed like other offshore structures to survive in the most extreme conditions. In such conditions energy levels at the surface may be as much as 10 times greater than the absorption limit, and energy shedding is the main requirement, not energy capture. North Sea experience of the corresponding high cost for survival may thus offer strong encouragement to the development of subsurface devices. These avoid the high penalties for exposure to very steep breaking waves, but still capture the relatively high proportion of the total energy resource found in the long period swell waves which penetrate to considerable depths without much attenuation. Another important area of overlap is the problem of slow drift oscillations affecting mooring system design, which is currently being studied co-operatively by a joint group of specialists concerned with applications to both wave energy devices and offshore installations. Finally it may be of interest to remark that there are even some areas in which the offshore industry can learn from the experience being gained in development of wave energy devices. Problems relating to directional properties of waves are an outstanding example. North Sea experience is indicating that directional distribution of wave loading can significantly affect the fatigue life of structures; TAG 2's progress in developing techniques for modelling the directional properties of wave climate may well be of considerable interest to offshore structure designers.

Dr J B Winter (ETSU)

It's quite likely that when you sit in your bath tonight you will think "I know something that works better than a duck or a raft or a water column". I have done it myself many times. If you do have a good idea we are receptive to it, but it is not easy. You have to convince us that you have thought about the engineering at full scale, the problems that will occur, the contribution that it can make, and in general whether it is feasible. It helps a great deal if you have done any hydrodynamic analysis of the idea, but simple calculations about weights of steel and distances that a wave might carry them aren't really very convincing at this stage in the game. We are not looking for at the least are practical people's ideas that have a decent chance of surviving and some promise of being cost-effective. If your idea meets these requirements, please send it to:

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Dr F J P Clarke

We plan to issue the Conference Proceedings to everyone who has attended the Conference. I think they will give the sort of detail that people have been asking for. The proceedings will be of fairly wide interest, not only in this country but overseas, and I think the Department of Energy may wish to publish them in a rather more permanent form later on. In addition, we hope to issue a more general paper on Wave Energy some time in 1979.
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