There are people\(^1\), until recently regarded as eccentric, who question our practice of treating as income those resources which our descendants will regard as capital. That apart, there are difficulties in satisfying exponentially increasing demands for power from finite supplies. The use of solar energy is one way of living on income. Another, which looks more attractive in the winter in Scotland, is the use of power from the waves at sea.
This proposal is divided as follows

Work done already

- Power levels 2
- Design problems 5
- The Design 6

Future work

- The Programme 9
- Facilities needed 11
- Test tank 11
- Electronics 12
- Staff 13
- Travel and Subsistence 13

- Research Experience 14
- Conclusion 15
- References 17
Power levels

We can estimate the amount of power in a wave train by calculating the change of potential energy as the water above sea level falls into the trough in front. Figure 1 shows part of a progressive train of sinusoidal gravity waves in deep water

\[ W = \text{width of wave front} \]
\[ \rho = \text{density of sea water} \]
\[ g = \text{acceleration of gravity} \]
\[ H_{tc} = \text{trough to crest height of waves} \]
\[ \lambda = \text{wave length} \]

The mass of water in the half sinusoid above sea level of width \( W \) is

\[ M = \frac{W \rho \lambda}{2} \frac{H_{tc}}{2} \]

The height of the centre of gravity above sea level is

\[ \frac{H_{tc}}{2 \sqrt{2}} \]

and it falls to an equal distance below.

The change of potential energy is

\[ \frac{1}{16} M \rho g H_{tc}^2 \]

It is well known that the frequency of gravity waves in deep water is

\[ f = \frac{1}{2\pi} \sqrt{\frac{g \lambda}{2\pi}} \]

Therefore the rate of transfer of potential energy or the power is

\[ \frac{1}{16\pi} M \rho g H_{tc}^2 \sqrt{g \lambda} \] (1)

(This approach to wave power prediction is simpler than that favoured by some fluid dynamicists. Its conclusions are supported by J. J. Stoker in his book Water Waves pp 47-51 and R. C. H. Russell in Waves and Tides p.163.)
Figure 1. Power transfer can be calculated from the change of potential energy as the water above sea level falls into the trough.
Analysis shown to me by Mollison indicates that the small reduction of potential energy of very steep waves due to their trochoidal shape is balanced by an increased velocity. Progressive waves transport energy across the sea and it is valid to say that the rate of transport of energy across some line is power. It is convenient to specify power density in kilowatts per metre of frontage.

The Institute of Oceanographic Sciences publish valuable data on waves using instruments developed by Tucker and Pierce. Draper and Squire analyse observations from Station India (59°N 19°W) which is characteristic of the western approaches to the Hebrides. The power is prodigious. Relationships between various wave parameters are explained in a useful paper by Tucker. For waves at sea it is more convenient to measure period \( T \) than wave length. Oceanographers like to use a height measurement, \( H_s \), the significant wave height, defined as the average height of the highest third of the waves.

We can get from \( H_{tc} \) of equation (1) to \( H_s \) via the root mean square displacement, \( D_{rms} \):

\[
H_{tc} = 2\sqrt{2} D_{rms}
\]

In a sinusoidal train

Tucker states that

\[
H_s = \frac{1}{4} D_{rms}
\]

so that

\[
H_{tc} = \frac{H_s^2}{2}
\]

To get from wave length to period we replace \( \lambda \) by \( \frac{2g}{T^2} \) to give the equation

\[
\text{Power} = \frac{1}{64\pi} \frac{W}{\rho g^2} T H_s^2
\]
Table 1. Scatter diagram for whole year observations at Static India reproduced from Draper and Squire. Each cell contains the occurrence in parts per thousand of a particular significant wave height and period.
combinations of significant wave height and period. Computer programs written for me by Buneman apply equation (2) to each cell of the table. We find that the average power over the whole year is 77 kilowatts per metre of frontage. Model tests suggest that the fraction of power which may be extracted depends on the depth of the installation. The fraction above a depth $d$ is $1 - \exp\left(-\frac{2\pi^2 d}{T^2 g}\right)$. We can draw up new arrays for different depths, in which each cell contains the contribution down to that depth. Unfortunately some of the power comes in uncomfortably large mouthfuls. A practical installation might need to be underdriven or submerged during the wildest weather. We can construct further arrays for different power limits in which the contributions of high power cells are reduced to some allowable maximum. Table 2 shows the results for combined depth and power limit reductions from three sea areas. Each entry gives the average annual power density in kilowatts per metre for the corresponding depth and power limit. Table 3 shows the relation between power density and wave period. Each column shows the average annual contribution for a given period interval.
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Station 'India' (59°N 19°W): total power = 77 kw/metre

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M.V Famita (57°30'N 3°00'E): total power = 36.8 kw/metre

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Sevenstones off Land's End: total power = 25.8 kw/metre

Table 2. Annual power density in kilowatts per metre for different combinations of depth and power limit.
Table 3. Distribution of annual power density with period.
Design Problems

A search of British Patents shows about a hundred proposals of varying feasibility for extracting wave energy. There was a spate of them after the First World War. Some of them are reviewed by Dhaille\textsuperscript{7} and Charlier\textsuperscript{8}. Flaps, floats, ramps, converging channels and liquid pistons are all advocated, and much ingenuity is expended in accommodating tidal rise and fall. Model tests on some proposals show poor efficiency. More recently Masuda\textsuperscript{9} and Yoshida\textsuperscript{10} describe the successful operation of equipment at low power levels for buoy and lighthouse use.

The essential problem is the conversion of dispersed random alternating forces into concentrated direct force by a mechanism which is efficient at low levels and yet robust enough to withstand the worst conditions. I believe that rigid connections to the sea bed are not possible on a large scale, and that the installation must be freely floating out at sea. As much of the equipment as possible should be below the surface. Concentrations of stress must be avoided, and power extracted smoothly.

Moving parts are against my religion but designs without them can only produce large volumes at low pressure differences and need some kind of transformer for efficient conversion. I am reluctantly forced to the conclusion that moving parts are unavoidable. But we should use rotating elements and protect mating surfaces from the sea. It will be difficult to gather in power from many small units moving independently, so there should be a common framework for a number of them. Waves transmit energy to one another with very high efficiency and we must let the water move in its usual circular pattern.
The first step is to get away from the idea of an object bobbing up and down although it is this aspect of waves which is most apparent. Use of the to and fro movement is much more rewarding. The energy passing through a vertical window is concentrated close to the surface and the water movements at all depths are of the same phase. I have tested a simple vertical vane pivoted about a horizontal axis along its bottom edge one eighth of a wave length down. It shows an efficiency of about 40%. Roughly 25% of the energy is transmitted onwards and about 20% back to the source. It works over a fair range of wave lengths. But it would be much more efficient if, somehow, it did not displace water astern and if the amounts of water displaced at any depth corresponded to amplitudes of water movements at that depth. Is a vane of this kind possible?

The Design

Consider the shape shown in section in figure 2. It rotates about centre 0 and absorbs power from waves coming from the right. Its stern is a half cylinder with centre 0 but from the bottom point it grows into a surface which is another cylinder centred about 0'. This surface continues until it reaches an angle $\theta$ to the vertical where it grows into a tangent, which is continued above the water. In my first model $0'$ is one half radius above 0 and $\theta = 15^\circ$. The efficiency for wave lengths about eight times the diameter of the small cylinder is over 80%. I will be testing the theory that a good vane should be able to extract nearly all the power contained in the band of water above its depth of immersion.

When the vane moves there is no change in the displacement of the water behind it and the changing displacements in front of it rise from zero at the bottom of the cylinders to amounts close to those in an approaching wave. This means that the shape has met the requirements. It is so far the most successful of various likely shapes that I have been testing in a wave tank. The models are coupled to a dynamometer consisting of two
Figure 2. An efficient vane shape designed to rotate about C. Waves come from the right.
moving coils in a magnetic field. Velocity signals from one coil are amplified and sent to the other so as to oppose movement. Velocity and force signals are multiplied to indicate power absorbed by the float and are compared with wave height measurements. This electronic simulation is very convenient for laboratory tests.

In full scale equipment at sea the random rotations of a vane will produce unidirectional pulses of water flow via a special pump shown in section in figures 3 and 4. The water is de-oxygenated and de-carbonated and recirculates within the system. The vane A is supported on and rotates about B, a hollow cylindrical member with paraxial ridges C on its surface. The outer faces of the ridges are supplied with high pressure water from an auxiliary pump and form hydrostatic bearings. Between them fit inward facing ridges D from vane A. The pair fit as a spline with close radial but very loose circumferential clearance. The spaces between C and D form four double acting pumps with non-return Macleod valves in the walls of the ridges C. These valves were originally developed for use with blood pumps. They consist of an elliptical butterfly plate across a conical passage. The centre of rotation does not pass through the centre of pressure and so there is a strong closing action. In the open state they offer minimum occlusion and are the most efficient non-return valves known to me. Working surfaces of the pumps are faced with ceramic and ground.

The member B forms a common back-bone for about forty vanes. An outer tube E contains manifolds connecting the spline pumps to a common turbine at the centre of the structure. The high pressure manifolds (400psi) are made from one metre diameter pipes F arranged round the inner circumference of E (see figure 4). Inside this ring of pipes is a large tube G which forms the low pressure manifold which returns water to the pumps from the turbine. The interstices between the pipes and the inner and outer tubes are filled with a mixture of lightweight concrete, glass fibre and resin.
Figure 3. A vertical section through vane and spline pump. For the North Atlantic the diameter of the cylindrical portion will be between 10 and 20 metres.
Figure 4. Enlarged section of the spline pump showing one ridge and the manifolds.
The ends of the pipes and tubes are swaged to allow a clamped connection of each length to the vertical fins H fitted between vanes. These fins house trim tanks, pressure smoothing accumulators, and the pipe work to couple each pump to the manifolds. At the bottom of the fins is concrete ballast to keep the centre of gravity well below the metacentric height.

A crucial problem facing the designer of wave power machinery is the provision of a steady reference against which his waves can act. Many approaches use connection to the land but in this design we are out at sea. The stable reference is supplied by the length, one half to two kilometres, of the structure. A short machine would pitch and heave and develop little force between vane and backbone. As the length is increased the installation samples a wider range of wave phases and becomes more and more steady. We can change direction by about 1° at each fin and give the structure an arc shape which will further increase stability in unidirectional seas. We obtain stability from the inertia of the ballast weight, from the drag of the deeper parts in quieter water, but mainly from the coupling of the machine to waves of opposing phase.

The only drawback to very great lengths is that the stress which can be developed by the worst conceivable wave rises with the square of the length. The worst predicted wave in 50 years in the North Atlantic has a trough to crest height of 34 metres and a period of 16·5 seconds. The surface particle velocity is 6·5 metres per second and the resulting stagnation pressure 21,000 Newtons per square metre. The shear forces and torsions which result from such monstrous waves are not a serious problem. It is the bending moments which are critical.
Future work

In the previous sections I have described an extremely efficient mechanism for getting power from test tank waves and outlined a design for full scale use at sea. It is now necessary to decide whether or not this country should spend very large amounts of capital. We are at a time when Middle East crude is no longer squirting up at ten cents a barrel, and the safety and security of nuclear power is being questioned. I hope that one day we will learn how to control a continuous fusion reaction and have a society that can be trusted with it. But any programme which pushes technology too fast, and in which the completion dates are set by political considerations, will suffer from expensive mistakes.

The capital cost of nuclear power is claimed to be about £300 per kilowatt. This figure refers to new plant and is not the ratio of total money spent on nuclear research to present capacity. It does not include air defence systems to shoot down Kamikazi hi-jackers nor the disposal of fast breeder residues. But it is the figure against which other sources must compete. It sets the cost of North Atlantic plant at about £15000 per metre. It limits the amount of steel which can be used to resist the bending moments caused by wave action.

The Programme

The initial stages of the project can be split into wet and dry phases. The dry phase consists of computer analysis of existing wave observations. Until now our predictions have been based on the scatter diagrams published in wave observation papers. These diagrams are the end product of an analysis programme and we should really go back to the raw data. The Institute of Oceanographic Sciences have been
collecting data for many years from sites around the British Isles. But it is kept in the form of chart records and only a little of it (usually storms of particular interest) has been digitised. The digitisation is done manually and is a back breaking job. I propose to build a video converter based on a television system. We have tried fitting a red filter to a television camera. We can suppress the red chart lines and see only the blue trace. We can run the charts through a recorder at high speed and punch out a number proportional to the time from the start of the line scan to the ink trace. My colleague Peter Buneman has already written software to analyse the digital data hitherto available. We will be able to produce statistics relevant to the wave power project from all suitable sites.

The wet part of the programme can be split into two parts. The first is the testing of various shapes of single vane unit in a variety of seas and at different depths. The instruments must be accurate so that small differences may be observed. With my present equipment these measurements are particularly troublesome because waves reflected from the model are returned to meet their maker and are either amplified or attenuated according to the phase of the return. Even without a model the wave heights in the tank can vary by 20%. I have found that the best vane shapes are themselves excellent wave makers and that when they are driven with a controlled torque rather than displacement the wave height stability is excellent. The tank manufactureres (Armfield) have shown some interest in this idea.

My present dynamometer is external to the model and coupled to it by elastic bands and universal joints. In the new dynamometers I plan to use commercial torque motors (Aeroflex) inside the model. We must greatly extend the sophistication of the electronics to include circuitry which simulates the operation of hydraulic valves, add acceleration terms
to the force feedback so as to change apparent inertia and have an
electrical control of model attitude. At present models are mounted
on rigid cone bearings. The magnitudes and phases of the forces on
these bearings must be measured and the effects of bearing movement
investigated.

The second part of the fluid dynamics programme is concerned with
the behaviour of multivane units. The multivane model must carry
internal dynamometers and be fitted with force sensitive cells between
each vane. We might be interested in two bending moments, two shear
forces, the tension and the torsion in each cell, but we can halve the
number of observations by assuming symmetry and concentrate on the
bending moments in the central section. We must provide different
amounts of compliance to allow the model geometry to change in response
to the waves. We must measure the pitch and heave and the fall in
efficiency of short lengths.

Facilities needed

Test tank.

An exhaustive study of the relationships of the many variables will
take thousands of tank hours. I propose to investigate first those
which seem most relevant and modify tests in the light of results.
Even so there must be a formidable amount of testing. Some of the single
vane work can be carried on in the tank in the Department of Fluid
Dynamics in Edinburgh but this tank is needed for other projects and I
have already ruthlessly exploited the goodwill of Dr Greated. The
multivane work needs a much wider tank and mixed sea wave makers. Big
mixed sea wave basins are expensive to hire (several hundred pounds per
day) and are all heavily booked for years ahead by oil companies.
It might be possible to get some time at night at Wallingford to do tests with very large waves but I am sure that it will be worth while building a small mixed sea tank in Edinburgh.

The tank would need beams across it to carry models and a sliding platform for observers. The wave makers would be electrically driven and would use the same principles of design as the power extracting vanes. Indeed some of the vane development can be done using transmitting rather than receiving components. There is a limit to the reduction in scale which is allowable. For wavelengths below 1.7 cm, surface tension forces predominate. I plan to use wavelengths from 20 cms to about 1 metre. For waves to behave like deep water waves the depth should be at least half a wave length. A depth of 60 cm will allow scale factors of 1 in 250. I believe that the design of beaches in a wave tank is extremely important. I intend to put a lot of effort into getting really good ones with maximal wave absorption.

The tank must be fitted with a comprehensive set of wave height measuring instruments. At present I use a light float which is coupled to a pair of moving coils stripped from meter movements. The velocity signals are A.C. coupled to eliminate drift but go through an active filter which has a flat pass band for the wave frequencies. They are integrated to give a position signal. This system is very sensitive and suitable for small long waves, but we need to build a capacitive wire system for shorter high waves. We will analyse wave height signals by the same techniques as are used by oceanographers for full scale waves.

Electronics.

My electronic workshop is well equipped but wave frequencies are lower than the range of most instruments and so I have asked for a low frequency function generator.
The most expensive item on the equipment list is the Tektronix digital processing oscilloscope. But it combines signal acquisition and monitoring, conversion to digital format, storage, processing and display, in one compact integrated package. It contains a small PDP 11 computer which can also be used for analysis of sea observations and general computation. It will be possible to extend the system by the addition of disc or tape backing store. I have asked for an extra £5,000 for this purpose.

We will build the dynamometers, wave maker electronics, wave height measuring instruments and some analogue computing and multiplexing circuits.

Staff.

I have reduced to a minimum requests for permanent staff but allowed a substantial amount for outside consulting. We need expert advice and help from a wide range of people in different disciplines.

I will need one research associate capable of doing original independent electronic design, one grade V technician, and some part time secretarial help.

Travel and Subsistence.

We shall need to visit our consultants, travel to other tanks for doing trials with very big waves, and spend time at sea on weather ships and oil platforms to supplement existing wave observations and get first hand experience of real sea conditions.
My Research Experience

I am mainly interested in the invention, design and making of instruments and tools. I started my career as an apprentice on the shop floor at Saunders-Roe, where I learned how to use every tool and machine from a file to a jig borer. I was given postings to the wind tunnel and the test tank where I worked on the very first Hovercraft. Much of my time was spent polishing mahogany or standing neck deep in freezing water, and I soaked up practical experience of the difficulties of applied research. I did electronic instrumentation for the Black Knight rocket project and then went to Cambridge in 1959 to read Natural Sciences. Richard Gregory took me on as a research assistant/inventor's mate to inject technology into the Psychological Laboratory.

We moved to Edinburgh in 1968 where I designed and built the mechanics and peripheral electronics of the Edinburgh robot (SRC Grant No. B/RG 1255). Other work that I have done includes astronomical instruments, video equipment for measuring babies' eye movements, apparatus for recording noises and breathing signals in birds' eggs, and computer teaching terminals. I hold patents on clamps, pinjoints, lathe tool grinding machines, and a touch sensitive screen. I have been studying wave power since October 1973.
Conclusion

At the end of this programme we will know enough to start a structural design of full scale machinery. We will know the power levels to expect and the forces which must be withstood. We will understand the behaviour of the plant under different sea conditions. Other problems will remain. There will be the spline pump seals and hydrostatic bearings which must give very long life despite structural flexing. There will be problems about corrosion and fatigue, barnacles and seaweed. But these are trivial compared with those of the fast breeder or fusion processes.

In common with solar, nuclear, and wind power, wave power comes at times not necessarily convenient to the user. Although its seasonal availability roughly matches demand, the problems of storage and distribution require careful attention, and will have to be taken into account in the overall planning. One promising approach is the electrolytic production of hydrogen from sea water. Present efficiencies are about 60% for this process, double that of thermal electricity generation. However, there is no thermodynamic limit to the efficiency and it has been suggested that high temperature electrolysis with catalytic electrodes may approach an efficiency of 100%. Storage of hydrogen in empty gas fields would be attractive. One kilowatt hour equivalent of hydrogen weighs only 30 grams. Compress it to thirty atmospheres and you can put one hundred kilowatt hours into a cubic metre. A floating installation could store several weeks worth and need not have any permanent connection to an under-sea pipe line. A long vessel mostly submerged requires very little power to move it slowly, and mobility allows us to retreat to calmer waters in winter, or discharge at shore terminals.
Wave power is clean, safe, permanent and uses relatively simple well-known technology. It will receive plenty of support after a bad nuclear accident but it would be prudent to have the basic research done now. We are particularly fortunate in our resources of wave energy. The approaches to the Hebrides are probably the best site in the world. A few hundred kilometres of installation could meet the total present electrical energy requirements of the U.K.

S. H. Salter

March, 1974
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