which is then recycled to react with the coal. There is a net production of hydrogen in this process which is the same for a given carbon consumption as in the steam gasification, with the alternative possibility of extracting this net yield in the form of methane. This process would be more attractive than steam gasification if it were not for the fact that a substantial fraction of the coal defies attack by the hydrogen and remains as a char. Success of the process depends consequently on the eventual possibility of being able to convert the char or otherwise use it as a source of carbon or energy.

## Technical requirements

The discussion so far in this article has concentrated on the problem of using nuclear energy to produce substitutes for the liquid and gaseous fossil fuels which play such a vital role in supplying our energy requirements. There are many other possibilities for using high temperature heat from nuclear reactors to carry out industrial processes on site and many of these may prove to be commercially attractive. The important fact which emerges in a consideration of these is that they will call for substantially higher helium temperatures than are needed for steam cycle electric power generation. In the latter case a reactor outlet temperature of 750° C is ample to generate steam at say 550° C. If, however, one is to provide heat for chemical processes ranging upwards from about 750° C we have to contemplate the achievement of reactor outlet temperatures of at least 950° C. This would allow for the use of an intermediate heat transfer circuit, with a primary heat exchanger transferring energy from the reactor helium to helium in the intermediate circuit, and a secondary process heat exchanger transferring heat from the intermediate circuit to the reacting materials in the chemical plant. The purpose of the intermediate circuit is to provide a safe isolation between the slightly radioactive primary helium and the hot, chemically active materials in the process plant (Fig. 2).

The feasibility of achieving helium temperatures from the reactor core in the region of 950° C has already been firmly established. In fact, the AVR at Jülich in the German Federal Republic is now operating at that temperature and in the Dragon Reactor Experiment helium emerges from the hottest channels at temperatures in the range 1,000°–1,100° C. Developments in fuel and core materials technology lead to the expectation of mixed helium outlet temperatures perhaps as high as 1,200° C in a few years. The problems of handling gas at such high temperatures elsewhere in the reactor primary circuit, and to a lesser extent in the intermediate circuit, are, however, quite formidable. Thermal insulation will be an aspect presenting many difficulties but undoubtedly the major problems will be associated with the interface heat exchangers, particularly the primary ones. It may be necessary to depart from the more conventional use of metals and go to ceramics or graphite in heat exchangers where the surface temperatures exceed about 1,000° C.

There would also be temperature problems to some extent in the cooler arms of both primary and intermediate circuits of nuclear process heat plants. This is because it is not convenient to have helium above about 350° C in those regions which contain the circulators, control machinery, and so on. The helium temperature drop across the process heat exchanger may be only in the range 200°–400° C so that it will emerge too hot for convenient recirculation. For this reason it would be desirable to take the helium from the high temperature process through a further stage of useful heat removal, most probably in providing the steam to generate electricity so that the plant serves a dual purpose.

## Availability of nuclear fuel

It has been assumed here that nuclear fission might be used as a more or less complete energy substitute for fossil fuels. Such an assumption, apart from technical and economic factors, is only valid if the exploitable resources of fissile material are many times greater than those of fossil fuels. The workable reserves of the latter are estimated to be about 200 Q which corresponds to about 2.5 million tonnes (Mt) of fission. In a situation in which sufficient fast breeders exist in sufficient proportion, this quantity of fission could be obtained from about 4 Mt of natural uranium which should be substantially less than that which should be ultimately available from high grade ores at around £10 per kilogram of uranium. Breeder reactors, in fact, could use uranium at a price two orders of magnitude higher, which would make available extensive low grade sources of uranium, notably the 4,000 Mt that exists in solution in the oceans. On this basis, the available fissile energy is incomparably greater than that contained in recoverable fossil fuels.

Unfortunately, the sodium-cooled fast breeder reactor on its own does not fit into the process heat strategy and would only contribute to it if the breeding gain of the fast reactors were sufficiently great to make up the breeding deficits of thermal-neutron high temperature reactors of at least equivalent energy output. (Exclusive use of sodium breeder of course would still permit the generation of hydrogen by the electrolysis route, but the installed capacity of the reactor plant would then be much higher than in the pyrolysis route.) Alternatively, a helium-cooled fast breeder reactor capable of attaining the same output temperatures would need to be developed. This is by no means out of the question.

In the absence of satisfactory fast breeders, however, a nuclear process heat strategy on a level of at least 1 Q per year could be supported with thorium cycle high temperature reactors operating in a thermal-neutral near breeding regime. These might require about 300,000 t of natural uranium and 15,000 t of thorium to yield 1 Q of heat and it would be economically feasible to use uranium from sea water in this application. To all intents and purposes this would constitute an indefinite supply of energy.

# Wave power

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*Solar energy is one form of income on which we can afford to live. Here is another proposal: the use of power from the waves at sea.*

THE amount of power in a wave train can be estimated by calculating the change of potential energy as the water in a wave above sea level falls into the trough in front of the wave (Fig. 1). If the sea water has a density $\rho$, and the width of the wave front is $W$, then the mass of water in the half sinusoud above sea level is

$$W\rho(\lambda/2)\,(H_{tc}/2\sqrt{2})$$

using the notation defined in Fig. 1. The height of the centre of gravity above sea level is

$$H_{tc}/2 \times 2\sqrt{2}$$

falling to an equal distance below. In such a situation the change of potential energy would be

$$gW\rho\,(\lambda/2)\,(H_{tc}/2\sqrt{2})^2 = W\rho g H_{tc}^2/16$$

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

$$(1/\lambda)\,(g\lambda/2\pi)^{1/2}$$

and, therefore, the rate of transfer of potential energy, or the power, is

$$W\rho g H_{tc}^2\,(g\lambda)^{1/2}/16\sqrt{2\pi} \qquad (1)$$

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. Power density can be specified conveniently in kW m$^{-1}$ of frontage.

The Institute of Oceanographic Sciences publish valuable data on waves using instruments developed by Tucker and Pierce[1]. Draper and Squire[2] have analysed observations from Station India (59°N 19°W) which is characteristic of the western approaches to the Hebrides. The amount of power is prodigious. The relationships between various wave parameters have been explained[3]. For waves at sea it is more convenient to measure the period, $T$, than the wavelength, $\lambda$. 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. In order to extend this discussion to include random waves at sea, $H_{tc}$ of equation (1) can be converted to $H_s$ using the root mean square displacement, $D_{rms}$ : in a sinusoidal train

$$H_{tc} = 2\sqrt{(2)}D_{rms}$$
$$H_s = 4D_{rms} \text{ (ref. 3)}$$
$$\therefore H_{tc}^2 = H_s^2/2$$

Wavelength, $\lambda$, can be converted to period, $T$:

$$\lambda = T^2 g/2\pi$$
$$\therefore \text{Power} = W\rho g^2 T H_s^2/64\pi \qquad (2)$$

The power which could be extracted can be predicted (Fig. 2 and ref. 2). Computer programs can apply equation (2) to each cell of Fig. 2. The average power over a whole year is 77 kW m$^{-1}$ of frontage. Model tests suggest that the fraction of energy which may be extracted depends on the depth of the installation.

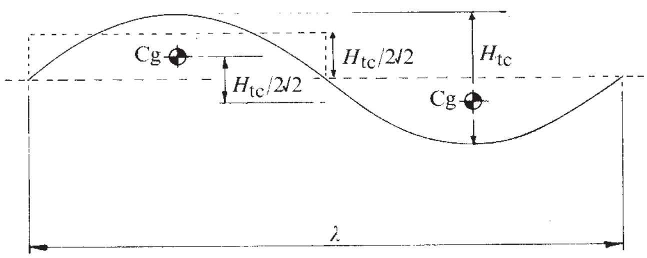


**Fig. 1** Part of a progressive train of sinusoidal gravity waves in deep water. $\lambda$, wavelength; $H_{tc}$, trough to crest height; Cg, centre of gravity.

Above a depth $d$, this fraction is $1 - \exp\,(-8\pi^2 d/T^2 g)$. New arrays can be drawn up for different depths, with each cell containing the contribution down to that depth. Unfortunately, some of the power comes in uncomfortably large amounts. A practical installation might need to be underdriven or submerged during the most severe weather. Further arrays for different power limits can be constructed with the contributions of high power cells reduced to some allowable maximum. Table 1 shows the results for combined depth and power limit reductions from three sea areas, and Fig. 3 shows the relationship between power density and wave period for the three observing stations.

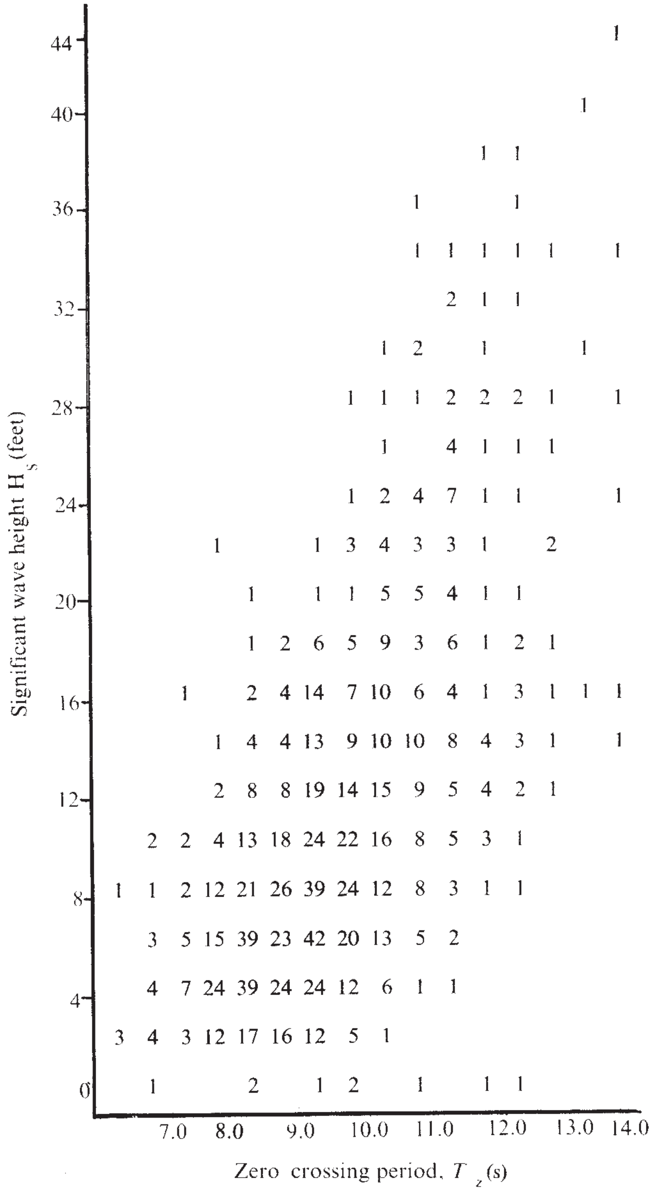


**Fig. 2** Scatter diagram for whole year observations at Station India reproduced from ref. 2, showing the number of occurrences, in parts per thousand, of waves of a particular height and period.

## Design problems

A search of British Patents shows about a hundred proposals of varying feasibility for extracting wave energy (see refs. 4 and 5). There was a spate of them after the First World War. 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, however, show poor efficiency. More recently, though, the successful operation of equipment at low power levels for buoy and lighthouse use, has been described. (Y. Masuda, and T. Yoshida, preprints.)

The essential problem is finding a method to convert dispersed, random, alternating forces into concentrated, direct force, using 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 should be extracted smoothly.

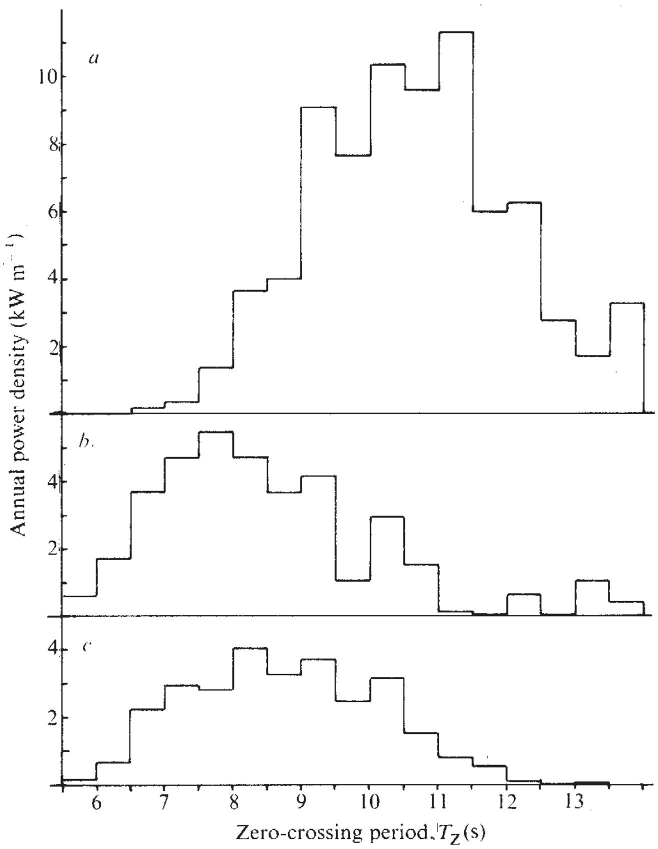


**Fig. 3** Distribution of annual power density with period: *a*, Station India; *b*, MV Famita; *c*, Sevenstones.

Moving parts, are generally troublesome, but designs without them can only produce large volumes at low pressure differences, and need some kind of transformer for efficient conversion. I must, therefore, reluctantly accept the conclusion that the use of moving parts is unavoidable. I think that it is best to use rotating elements, and to protect mating surfaces from the sea. It will be difficult to gather in power from many small units moving independently, and so there should be a common framework for a number of them. As waves transmit energy to one another with very high efficiency, the water must be allowed to move in its usual circular pattern.

The first step is to get away from the idea of an object bobbing up and down, although, of course, it is this aspect of wave motion which is most apparent. Use of the to and fro movement would be 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 wavelength down. It works over a reasonable range of wavelengths and it shows an efficiency of about 40% when driving an electronic dynamometer. Roughly 25% of the energy is transmitted onwards, and about 20% is transmitted back to the source. It would, however, be much more efficient if, somehow, it could be designed so that it did not displace water astern and so that the amount of water displaced at any depth corresponded to the amplitudes of water movements at that depth. But is a vane of this kind possible?

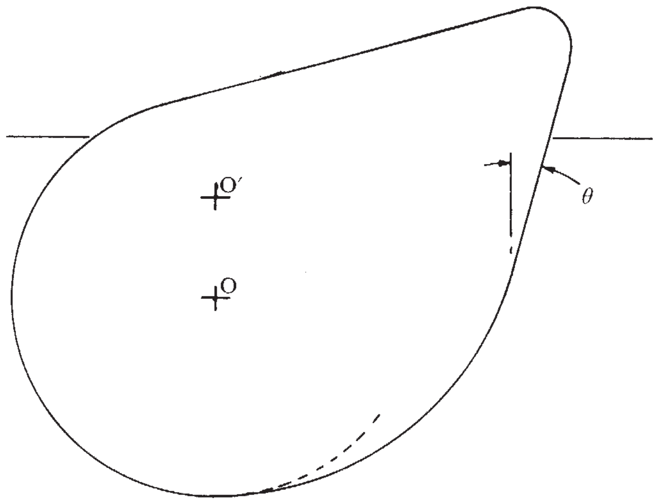


**Fig. 4** An efficient vane shape designed to rotate about O. Waves come from the right.

## The design

Consider the shape shown in section in Fig. 4. It rotates about its centre, O, and absorbs power from waves coming from the right. Its stern is a half cylinder centred at O, but from the bottom point it grows into a surface which is another cylinder centred about O′. This shape continues until it reaches an angle θ, to the vertical, at which point it develops into a tangent, which is continued above the surface. In my first model, O′ is one half radius above O, and $\theta = 15°$. The efficiency for wavelengths of about eight times the diameter of the small cylinder

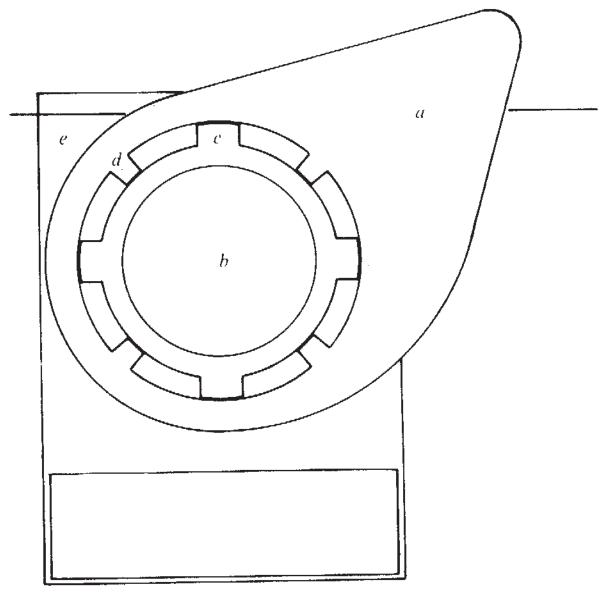


**Fig. 5** A vertical section through vane and spline pump. *a*, vane; *b*, a hollow cylindrical member; *c*, paraxial ridges; *d*, inward facing ridges on the vane; *e*, vertical fin between this vane and the next. For the North Atlantic the diameter of the cylindrical portion will be between 10 and 20 m.

is over 80%. I intend to test the theory that a good vane should be able to extract nearly all of 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 the approaching wave. This means that the shape meets the necessary requirements. It is, so far, the most successful of the likely shapes that I have been testing in a wave tank. The models are coupled to a dynamometer consisting of two 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 vane 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 through a special pump (Figs 5 and 6). The water is deoxygenated and decarbonated, and recirculates within the system. A vane is supported on, and rotates about a hollow cylindrical member with paraxial ridges on its surface. The outer faces of the ridges are supplied with high pressure water from an auxiliary pump, and they form hydrostatic bearings[6]. Between them there are inward facing ridges from the vane. The pair fit as a spline with close radial, but very loose circumferential clearance. The spaces between the inward and outward facing ridges form four double acting pumps with nonreturn Macleod valves[7] in the walls of the ridges on the cylinder (Fig. 5). 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 nonreturn valves that I know of. The working surfaces of the pumps are faced with ceramic, and are ground.

**Table 1** Annual power density for different combinations of depth and power limit.

| | Depth (m) | Power limit (kW m$^{-1}$) 100 | 200 | 300 |
|---|---|---|---|---|
| *a* | | | | |
| | 5 | 22.7 | 24.0 | 24.1 |
| | 7.5 | 29.0 | 32.3 | 33.0 |
| | 10 | 33.5 | 38.6 | 40.0 |
| | 15 | 39.1 | 47.0 | 49.8 |
| | 20 | 42.4 | 51.9 | 56.0 |
| | 25 | 44.1 | 55.0 | 59.8 |
| *b* | | | | |
| | 5 | 16.4 | 16.5 | 16.5 |
| | 7.5 | 20.8 | 21.5 | 21.5 |
| | 10 | 23.8 | 25.1 | 25.1 |
| | 15 | 27.1 | 29.4 | 29.8 |
| | 20 | 28.7 | 31.8 | 32.4 |
| | 25 | 29.5 | 33.0 | 33.9 |
| *c* | | | | |
| | 5 | 10.9 | 11.0 | 11.0 |
| | 7.5 | 14.2 | 14.5 | 14.5 |
| | 10 | 16.6 | 17.1 | 17.2 |
| | 15 | 19.3 | 20.7 | 20.8 |
| | 20 | 20.9 | 22.7 | 22.9 |
| | 25 | 21.8 | 23.9 | 24.2 |

*a*, Station India (59°N 19°W), total power = 77 kW m$^{-1}$; *b* MV Famita (57° 30′N 3°E), total power = 36.8 kW m$^{-1}$; *c*, Sevenstones of Lands End, total power = 25.8 kW m$^{-1}$.

A common back bone for about 40 vanes is provided by the cylindrical member. An outer tube contains manifolds connecting the spline pumps to a common turbine at the centre of the structure. The high pressure manifolds (400 pound inch$^{-2}$) are made from 1 m diameter pipes (Fig. 6). Inside this ring of pipes is a large tube which forms the low pressure manifold and which returns water from the turbine to the pumps. The interstices between the pipes and the inner and outer tubes are filled with a mixture of lightweight concrete, glass fibre and resin. The ends of the pipes and tubes are swaged to allow a clamped connection of each length to the vertical fins fitted between vanes (Fig. 5). These fins house trim tanks, pressure smoothing accumulators, and the pipe work which couples each pump to the manifolds. At the bottom of the fins concrete ballast keeps the centre of gravity well below the metacentre.

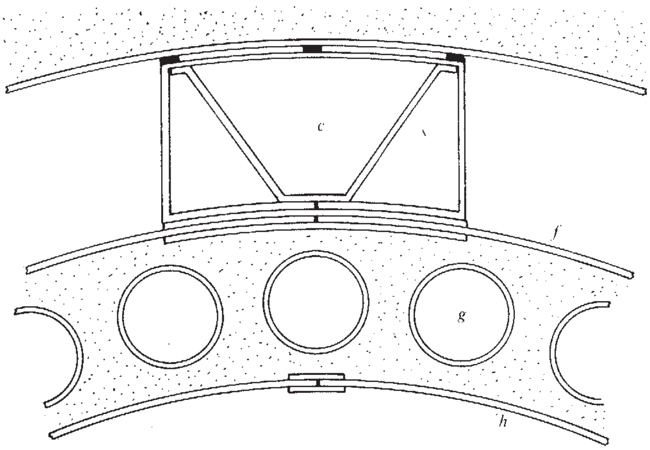


**Fig. 6** Enlarged section of the spline pump, showing one ridge and the manifolds. *c*, Paraxial ridge shown in Fig. 5; *f*, outer tube containing manifolds; *g*, pipes of 1 m diameter; *h*, large tube, forming the low pressure manifold.

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 this design would operate out at sea. A stable reference can, however, be supplied by using a structure 0.5–1 km long. 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. Stability is obtained from the inertia of the ballast weight, from the drag of the deeper parts in quieter water, and from the coupling of the machine to waves of opposing phase. The only drawback to using very great lengths is that the stress which can be developed by the worst conceivable wave rises with the square of the length. The largest predicted wave in 50 years in the North Atlantic would have a trough-to-crest height of 34 m and a period of 16.5 s. The surface particle velocity would be 6.5 m s$^{-1}$ with a resulting stagnation pressure of 21,000 N m$^{-2}$. The shear forces and torsions which result from such monstrous waves would not be the most serious problem. It is the bending moments which are critical, and which set limits to the lengths which can be used.

## Energy storage

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. Electrolytic production of hydrogen from sea water looks promising in this respect.

The installations could be self propelled. They could move in line ahead, a low drag condition, out into the Atlantic, turn abreast to the waves, and be slowly driven back by wind and wave thrust, storing hydrogen on the way. Most of the hydrogen could be discharged at a shore terminal, leaving enough to get out to sea again. This mobility gives many advantages, and obviates the mooring problem.

Wave power is clean, safe, permanent and uses relatively simple and well known technology. It is likely to receive plenty of support after a bad nuclear accident but it would be prudent to have the basic research done now[8]. 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 UK.

I would like to thank the University of Edinburgh and the Nuffield Foundation who supplied my workshop facilities, the National Institute of Oceanography, and my colleagues Drs O. P. Buneman, C. A. Greated, D. Mollison, and J. W. Ponton, for their help and criticism, and Sheikh Ahmed Zahi Yamani and OPEC for their continuing encouragement.

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# Prospects for hydrogen as an energy resource

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*Storing energy in the form of hydrogen is an attractive possibility to provide fuel for transport and the reduction of iron ore. The main obstacle is the expense of the electricity needed to synthesise hydrogen.*

THE recent restrictions placed by the producing nations on the global supply of oil, and the growing realisation that world demand for oil and natural gas is increasing at a rate faster than the discovery of new resources, have focused attention on the need for alternative energy resources. There is no immediate crisis in terms of proven oil and gas reserves, but development towards alternatives should start soon if the new technology is to be widely available when it is needed. As an indication of the time scale required for the introduction of a new energy resource it is worth pointing out that 18 years after the commissioning of the first Calder Hall reactor, nuclear power has still not achieved more than 10% penetration of the market for electricity production in the United Kingdom.

Forecast of the time when the rate of production of oil will begin to decline vary over a considerable period, and might be as early as the mid-1980s if historic trends continue: it is assumed here that the decline will certainly be evident by the end of the century. As we approach that time two primary energy sources are likely to assume over-riding importance: coal and nuclear fission. But synthetic secondary fuels are likely to be needed for special purposes and hydrogen could be one of these. Hydrogen is best regarded as a potentially attractive means of storing and transporting energy which can be provided from a variety of primary sources: it is therefore more analogous to electricity than to oil, although some of its most rewarding applications may be as a substitute for oil products. The hydrogen would be produced from water and in this process more energy is expended than is recovered in burning the hydrogen subsequently; this point will, however, assume decreasing importance as the production of hydrogen moves progressively towards dependence on renewable energy resources. Hydrogen attained industrial importance a few decades ago when coal provided the primary energy for water splitting; now it is produced in larger quantities from natural gas and oil: if it is to achieve the even more widespread use implied by the 'hydrogen economy' then it will have to be based on the energy input from nuclear fission reactors and subsequently there could be a gradual transition to nuclear fusion and solar energy resources.

Much has been written on the subject of hydrogen over the past few years, culminating in the nearly 100 papers at a recent conference devoted exclusively to the subject (see ref. 1). It is not possible to review all of this work here; I shall attempt rather to take a realistic view of the overall prospects and of some of the problems to be overcome.

## Markets for hydrogen

As oil becomes a scarce resource and nuclear energy takes over, in principle all major energy users except air transport could be satisfied by the increased availability of relatively cheap electricity—much has been written on the advent of the all-electric economy. This would also require however, the development of major new technology, of which the long range electric road vehicle is perhaps an outstanding example. It is possible that when the costs of transmission and storage are added to the cost of production, under some circumstances hydrogen may become competitive with electricity for many uses. This possibility of interchange and substitution between several energy sources renders the whole subject very complex: the forecaster finds it fascinating and yet extremely hazardous.

One of the largest new uses for hydrogen could be as a fuel for road transport: in the United Kingdom this might ultimately amount to a requirement of several million tons per year. The competition will however be strong among several candidate fuel supplies:

- allocate oil to road transport as a priority item
- electricity, based on advanced batteries for energy storage on the vehicle
- liquified methane (natural or substitute)
- methanol
- hydrogen

Each of these possibilities has its advocates and, apart from the first item, each has a considerable range of development problems to be overcome. Perhaps a mixture of several solutions is the most likely outcome, with each fuel taking a particular share of the total market.

Practical experience has shown that the use of hydrogen requires little alteration to the internal combustion engine on