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THE OCEAN AS A POWER RESOURCE†

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(*Received February* 8, 1972)

This paper considers the feasibility of tapping a number of potential sources of energy in the oceans, assesses their magnitude in relationship to projected world needs, and discusses some means for avoiding environmental degradation.

SOURCES OF ENERGY

After decades of anticipation we may now be close to the ability to extract substantial amounts of energy from the sea. Serious efforts are underway in several countries to use the "free" energy of tidal oscillations induced by the motions of the moon and sun. This paper explores methods for tapping another free resource, the 80 trillion kW of solar fusion energy that is absorbed by the deep oceans and the atmosphere above them.

Even though only a small portion of this radiative flux is directly deposited in the sea, the total energy budget of the ocean is large compared to man's needs. Some of the incident solar energy establishes and maintains thermal gradients. Water is evaporated, condensed and precipitated nonuniformly and establishes salinity differences. The runoff of rain falling over the continents also injects not only fresh water but its burden of dissolved and suspended chemicals. Kinetic energy is stored in certain slowly moving currents resulting from these density gradients. Most of the kinetic energy input, however, results from direct interactions with the atmosphere. Wind stress drives surface waves and currents.

We see the oceans then as a storage device with an inventory of several years of solar energy in the form of stable thermal and salinity gradients and water in motion. The system is in general steady state through processes such as evaporation, mixing, viscous losses and sedimentation.

Before we consider the feasibility of extracting significant quantities of energy from this storage pool, it would be prudent to attempt to determine the approximate magnitude of some of these natural processes. With the unpleasant examples of man's tampering with natural energy budgets, it seems that as a first principle we should assure ourselves that our proposed alteration of the natural processes is not a substantial disruption.

Some estimates of the dissipation rates of solar power in the ocean are shown in Figure 1. Tidal dissipation and man's needs extrapolated to the year 2000 are shown for comparison. It should be clear that, at best, all of these values, including man's needs less than 30 years hence, are poor guesses. All of the calculations in the ocean involve fictitious average values based upon very few measurements. Perhaps the only safe assumption possible from numbers like these is that large

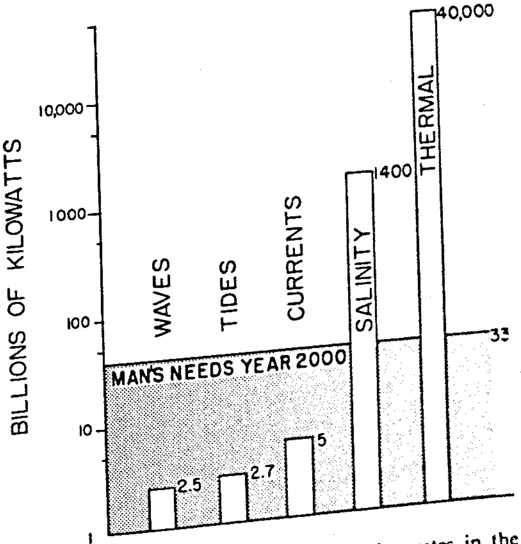

FIGURE 1 Estimates of power dissipation rates in the oceans.

† Based on a paper presented at the A.I.C.E. Symposium on Novel Energy Sources in March, 1971 (Houston, Texas).

renewable energy sources exist but that the rate of energy flux in a useful form is probably not as large as all of man's foreseeable power needs.

One of the problems in economical utilization of "free" energy is its low density. Only when some natural concentration process exists, such as a swiftly flowing stream or the peculiar topographic configurations that cause tidal amplification, do we find the capture useful. Thus we need to look for locations where natural processes have increased the available power density. Salinity gradients in the open ocean are miniscule, but large rivers discharging into the ocean locally provide just the type of gradient concentration we might seek.

WAVE POWER

Another obvious concentration is in wind waves and swell, limited to the top few per cent of the ocean volume. To illustrate the magnitude of energy density of waves, Figure 2 shows the nuclear ship

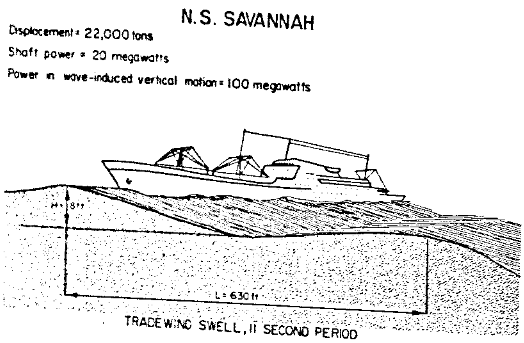

FIGURE 2 Comparison of ship propulsion power with wave motion power.

Savannah steaming parallel to a long-crested tradewind swell of reasonable proportions. We see the rather surprising result that the power in the vertical response of the ship to this swell exceeds by a factor of five the shaft power produced by her reactors. Therefore, in extensive parts of the world, wave energy density reaches interesting values. Also wave power is not only renewable and more persistent than the wind but, interestingly, is "self-healing". That is, much of the wave energy that is removed while the waves are still being acted upon by the wind is soon restored.

Any attempt to construct a mechanical device to extract energy continuously from waves is faced with certain engineering problems. Common wave heights are relatively low in terms of water head and, hence, cannot be effectively used. Wave motions also are oscillatory and vary over broad ranges of amplitude and frequency. The coupling mechanism should be such that the device will usefully respond to the smaller waves without suffering destructive accelerations from large storm waves. The power output in most systems will necessarily be variable so that some form of storage or flexibility will be required in the system.

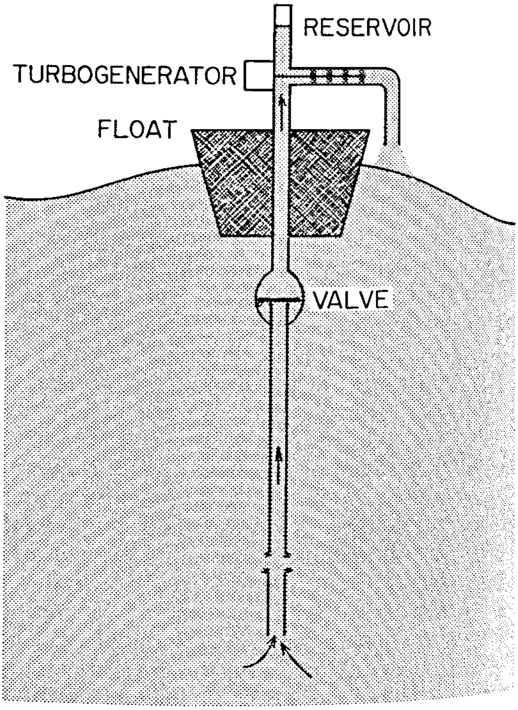

FIGURE 3 Schematic representation of a wave-powered generator.

An illustration of a simple solution to these problems is a device under development at Scripps Institution of Oceanography. It is a pump consisting of a vertical riser containing a flapper valve and a buoyant float at the surface as shown in Figure 3. Slack tethered, it responds directly to wave motions. A model continuously discharged about 40 cf/h against a 5-ft head through a 2-in. pipe for long periods. A 5-kW prototype is in final design. The advantages of this system over many proposals for wave power extraction are that it is responsive to a broad portion of the wave spectrum and that it amplifies the pressures involved in the wave displacement for more efficient power generation. Figure 4 shows a typical power spectrum of wind waves and swell. On this plot are shown T_H, the natural period of the entire system in vertical motion with the pipe filled with water to the operating level and blocked, and T_M, the natural period of oscillation of the water within the pipe. During operation, the flapper valve closes for approximately half of the wave cycle, forcing the water in the pipe to follow the motion of the float. As the float changes direction of motion, the water continues upward on an inertial course, which

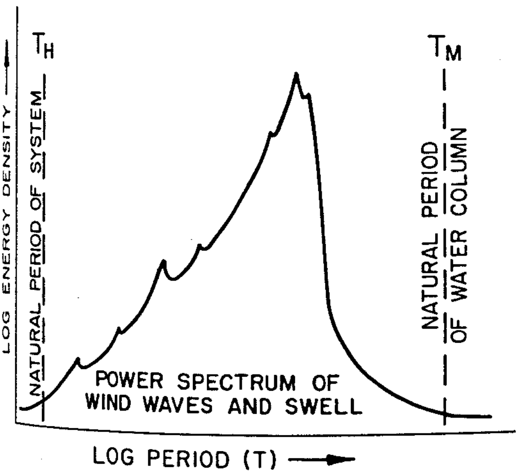

FIGURE 4 Response of a wave-powered generator to a random sea.

carries it higher than the wave height. Subsequent cycles raise it successively higher until a pressure suitable for power generation is reached. The wave train maintains flow at this pressure. The system can also be closed and be either singly or doubly rectifying, and the pressure is limited only by the length of the vertical pipe.

Where winds are constant and large waves can be regularly anticipated, significant quantities of energy probably can be extracted.

As another example, Figure 5 shows the general arrangement of a hydroelectric generating plant in which the head of water is maintained by the net momentum transport of shoaling and breaking waves, which is concentrated by a converging channel.[1]

All of the power sources in the ocean, with the possible exception of waves in trade wind areas and some thermal gradients, are sufficiently unstable to prevent extracting energy at a constant rate. However, it may be possible to use some of the characteristics of the ocean to simplify surge

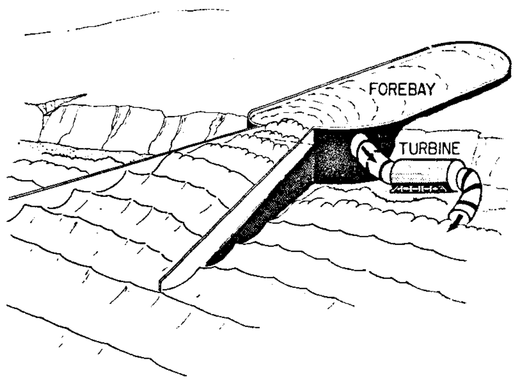

FIGURE 5 Power generation utilizing momentum transport of shoaling waves.

storage. Figure 6 suggests a storage device located on the ocean floor in which electrical energy is utilized to generate hydrogen and oxygen in a high pressure electrolysis unit. The gas is stored by simple water displacement, eliminating the cost and hazard of the pressure vessels that would be

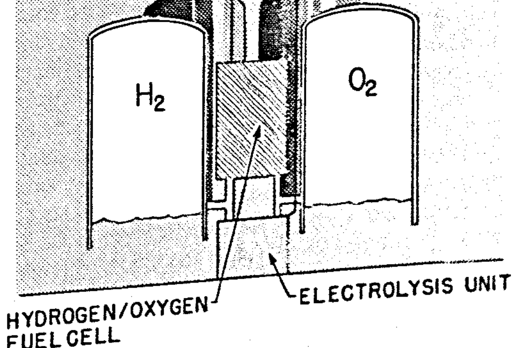

FIGURE 6 An underwater power storage device for output smoothing.

necessary on land. A constant power output is delivered by a hydrogen/oxygen fuel cell, which also regenerates the fresh water for the electrolysis.

POWER FROM THERMAL GRADIENTS

Because thermal gradients in the ocean are so stable they have continued to attract engineering effort to utilize the differences of up to 20°C that exist in close proximity in many parts of the world. The work of Claude in Cuba earlier in this century and the recent efforts of his successors at Abidjan in Western Africa were based on a low pressure water vapor system as shown in Figure 7. Both projects were abandoned because of the difficulty of installing and maintaining through the surf zone the long intake pipe for the cold deep water.[1] This problem is largely caused by a cultural requirement that power plants be built on shore. It could be overcome by moving the whole system offshore in a floating structure where the intake pipe is of minimum length and where it can be freed from destructive wave forces. Based upon current studies on the circulation of deep water within coral atolls, it may be possible to drill an atoll and use the thermal gradient between deep internal water and the lagoon to generate power without the necessity for intake piping.

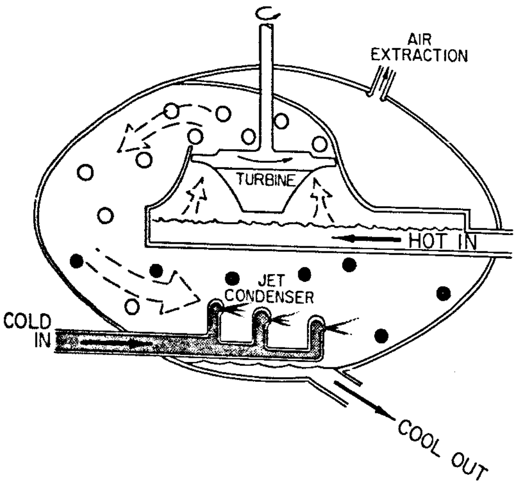

FIGURE 7 Low pressure turbine for extracting energy from small thermal gradients.

The atoll site offers an opportunity for observing the ways in which the total power extraction can be enhanced. Pumping deep, nutrient-rich waters to the surface allows the fertilization of the lagoon and the ability greatly to increase the productivity of marine plant and animal production. The natural restraint of the lagoon might make feasible the selective breeding of "domestic" seafood that would survive preferentially in this aquatic farm. By using a heat exchanger in the cold water and a fresh-water instead of a sea-water jet condenser in the steam generating plant, fresh water could be produced in large quantities. Power generated in this manner could be utilized locally for chemical extraction from seawater. If we consider the fertilization and the desalinization as power outputs of the system, this thermal gradient plant may become competitive with more conventional sources. In this connection it should be pointed out that when cold deep water is used for heat rejection in conventional power plants, not only is thermal pollution greatly reduced or eliminated, but, also, we are tapping the vast store of thermal energy in the sea at the higher efficiencies characteristic of conventional power plants.

Another large stable thermal gradient exists between the relatively warm water below the polar icecaps and the cold air above. It has been proposed to utilize this gradient to meet local power needs. A thermal generating plant based upon an ammonia cycle is suggested in Figure 8.

Currents, internal waves, and oceanic salinity gradients, although they represent large energy reservoirs and dissipative mechanisms, appear too diffuse for economical energy extraction. Even the highest velocity currents require immense turbines

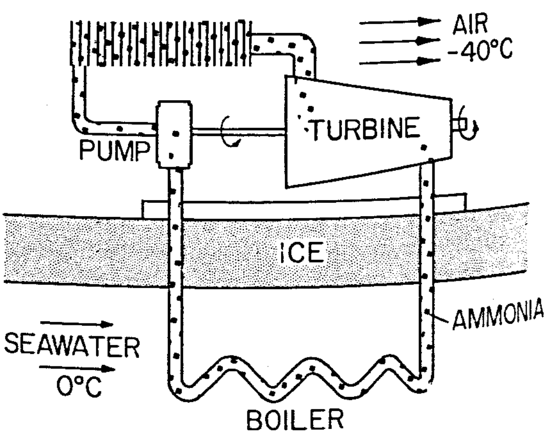

FIGURE 8 An ammonia vapor generation system utilizing gradients across polar ice.

for significant generation, and, contrary to some proposals, venturi constrictions are not effective in a free stream. The sharp salinity gradient possible at the mouths of rivers discharging into the sea is of interest, however. The potential energy in this cell, represented by the osmotic pressure, is equivalent to the river arriving at its mouth at an elevation of more than 700 ft above sea level! This is a large fraction of the head utilized for hydroelectric generation, even for a heavily exploited river like the Columbia. Clearly, if future technology allows the conversion of this potential to usable power, a vast resource exists.

FUSION FUEL EXTRACTION

It appears reasonable that the greatest power resource in the ocean may be nuclear. Projections of power needs into the next century make it very apparent that nuciear fusion may be the only possible solution to diminishing supplies of fuel. Every proposed cycle for fusion utilizes some combination of deuterium, lithium or tritium. Deuterium is readily obtainable from seawater and it has been estimated that there is sufficient to supply fusion energy to meet man's present needs for over 40 billion years. Lithium is the fifteenth most common element in seawater and its supply exceeds the known land reserves by more than a factor of two. Tritium would most likely be bred in a lithium blanket surrounding the reactor.

It is possible, therefore, to project a nonpolluting world power generation scheme in which fusion fuels are concentrated in conjunction with atoll fish farms and then consumed in generating plants close to population centers. These thermal plants will in turn pump up deep cool water for their condensers which can be discharged at ambient temperatures to avoid thermal pollution of coastal waters and can produce fresh water as a byproduct. In this view, the oceans may hold the promise for almost unlimited fuel supplies for safe, non-polluting energy generation, and at the same time, help meet increasing demands for food and clean water.

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