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Ocean Energy: Forms and Prospects

John D. Isaacs and Walter R. Schmitt

Man is rapidly emerging as a geophysical and geochemical force approaching the magnitude of other great natural systems. Energy consumption by humans in the early 21st century is projected to exceed individually the natural energy flux of rivers and tides, that of all the waves and swell and currents of the oceans of the planet, as well as the total flux of geothermal heat. The energy sources potentially available to humans in the next few centuries range from the meager to the vast. Indeed, even considered over the several billion years during which this planet may remain habitable, some of these energy sources are huge (Table 1). There are the nuclear materials sequestered by the planet—the light fusionable elements and the heavy fissionable nuclei. There is the vast outpouring of solar energy, of which the earth intercepts a billionth part or less. And there is the "fossil" kinetic energy with which the earth and moon spin and which terrestrial and marine tides slowly degrade.

Most of these energy sources, fossil and contemporary, display a flux to other forms. Reservoirs exist of each of these sources or some derivative form, and the oceans are profoundly involved in these fluxes and reservoirs. Thus, in addition to the fossil organic fuels that the ocean sediments may hold, the seas of this planet are collectively a broad and important realm that must be considered in assessing future power sources and power generation. Not yet clear are the comparative values of these potential marine sources, the usable forms of marine power and optimum approaches to obtaining it, and the probable ultimate contributions of marine power toward meeting humanity's seemingly insatiable appetite for energy.

Summary. The nature and distribution of power sources of the sea other than petroleum are discussed, along with possible entrées for their use. Waves, tides, currents, and salinity and temperature gradients all have the potential to contribute useful power. Submarine geothermal sources, salt domes, ice, and other marine-associated concentrations may be more important. There are opportunities to employ these marine power resources directly rather than for contributions to power grids or power-intensive products. Ancillary employment of the seawater as a coolant and of the sediments below the seabed for the disposal of nuclear wastes may be even more important uses than employment of the power that the sea contains.

We will introduce this topic with some brief comments on the sea as a source of nuclear fuels. The bulk of the article will be devoted to the primary nonpetroleum power sources of the sea, which can be classified as mechanical (waves and swell, tides, and currents), chemical (salinity gradients and biomass), and thermal (temperature gradients, including ice). Each of these has the potential for yielding useful power (see Fig. 1), and each is characterized by a particular geographic distribution, reservoir, natural flux, energy density, range of possible approaches, and potential response to utilization. Finally, we will discuss aspects that may be of more immediate importance, including submarine geothermal springs, salt domes, coolant sources, and radioactive waste disposal.

Marine Nuclear Resources

Fissionable and fusionable elements are present in the sea in varying but high total abundance, although some are in low concentrations. The total amount of fissionable uranium and thorium in seawater is sufficient to sustain the estimated 21st-century level of power production for some millions of years. The fusionable species lithium and deuterium are present in sufficient quantity to sustain that power level for the remainder of the life of the solar system, while the hydrogen present could supply the same power for many times that period. Constraints to the utilization of these sources are, of course, the yet-to-be-demonstrated feasibility of controlled fusion and the problem of safe disposal of highly radioactive fission wastes.

Natural marine processes, often organic, tend to increase the concentrations of uranium, thorium, lithium, and perhaps deuterium by at least several orders of magnitude. When these concentrating processes are better understood, it may be possible to enhance the supply of these elements inexpensively, and initially wherever seawater is handled in large quantities, such as at seawater-cooled power plants. Submarine monazite sands are relatively common in coastal regions, and mining for the thorium that they contain can add substantially to the available inventory of fissionable elements. Their presence is traceable through detection of thorium daughter products in seawater and bottom sediments.

John D. Isaacs is a professor of oceanography and director of the University of California's statewide Institute of Marine Resources. Walter R. Schmitt is a specialist in oceanography. Both are at Scripps Institution of Oceanography, La Jolla, California 92093.

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Waves and Swell

Rarely is the ocean surface undisturbed by wave motion. Waves and swell—degraded solar energy, created through the agency of the winds—are steadier than the winds, for they convey wind energy over immense distances with only modest dissipation in open deep water. Although conspicuous and impressive, they do not contain as much energy as common judgment would attribute to them. Wave-energy fluxes in the open sea or against coasts may vary from a few watts to a megawatt or more per meter. They are least in summer and greatest in winter and in the zones of the westerlies and the trade winds (*1*). Knowledge of wave conditions in the tropical and southern oceans is still sketchy, however. Even in the principal areas, the great variability of wave-energy flux imposes severe problems in its utilization. These problems stem from both this irregularity and the requirement that any generator would have to survive extreme storm waves.

Fundamental approaches to the utilization of wave energy have been discussed elsewhere (*2*). These approaches involve systems that link into wave displacement, rotation of the wave surface, orbital motion, nearshore bore formation, wave form, or phase velocity, in the order of their increasing sophistication and complexity.

Vertical displacement is perhaps the simplest entrée into wave motion. Whistler buoys and the lighted navigational buoys presently manufactured by the Japanese utilize this motion (*3, 4*), and a larger scale power plant is being built on this principle in Japan. The power represented in the up-and-down displacement of a ship in a seaway ordinarily exceeds that used for its propulsion. Roll-and-pitch motions also represent a considerable power flux, and passive hydraulic stabilizers can yield some useful power as a by-product. Most proposals for harnessing wave power for use in ships have envisaged massive articulations within or of the ship's hull for the generation of hydraulic or other forms of power. Such features of ship construction are ordinarily to be avoided, and it is not certain that the quantity of wave power generated in a ship could make a significant contribution to its propulsion, although it should be easy to produce enough power for "hotel" purposes and possibly even for the propulsion of barges transporting inexpensive bulk cargos, as discussed later. Wave motion has been employed for the propulsion of small boats (*5*).

A wave-operated pump, developed at the Foundation for Ocean Research in San Diego (*6*), is based on the inertial interaction of two integrated systems—a buoy connected to a long vertical pipe flooded with water (Fig. 2). This water column responds to such low frequencies that it cannot follow the sea surface when uncoupled from the pipe and float. Controlled by a simple check valve, the water in the pipe is forced to accelerate upward by the motion of the buoy, and it continues to flow upward as the buoy and pipe drop. The hydraulic pressure in a reservoir then increases and is limited only by the maximum vertical acceleration and the pipe length. For a 100-meter pipe and a maximum acceleration of $0.5g$, the pressure will increase to about 5 atmospheres. Before this pressure is reached, the water is allowed to escape continuously under pressure and to interact with a turbine or Pelton wheel, and power is generated. The efficiency of this system, which has been tested at sea, is estimated as 25 percent of the incident power. The virtues of this system are its simplicity, relative invulnerability, response to a broad band of wave frequencies, and multiplication of wave pressure. Similar multiplication of wave pressure and broad spectral response can, of course, be achieved by allowing floating bodies responding to waves to act on pistons or bellows, but it remains to be seen whether such systems can survive time and extreme conditions.

Table 1. Order-of-magnitude estimates of the energy of some natural events, fluxes, and human activities. Asterisks denote fluxes for 1 year. It appears that the ocean's hydrogen could fuel the sun's radiation process for 1 year or sustain a leap for 10^{41} fleas.

Energy source or sink	Energy (ergs)
Big bang	10^{75}
Radio-galaxy emission	10^{62}
Supernova	10^{50}
Ocean's hydrogen in fusion	10^{41}
Sun's radiation*	10^{41}
Earth's rotation	10^{36}
Ice-age latent heat	-10^{33}
Marine uranium	10^{33}
Insolation to the earth*	10^{32}
Near-surface wind flux*	10^{29}
Salinity-gradient flux*	10^{28}
Thermal-gradient flux*	10^{28}
Marine biomass*	10^{28}
A.D. 2050 electricity demand	10^{28}
Wave flux*	10^{27}
Volcanic detonation	10^{26}
Large salt dome	10^{26}
Tabular-iceberg heat sink	-10^{25}
Major ocean-current flux*	10^{25}
Feasible tidal power*	10^{25}
Largest H-bomb	10^{24}
Tornado or thunderstorm	10^{22}
Tsunami	10^{22}
Lightning flash	10^{17}
Human daily diet	10^{14}
Can of lighter fluid	10^{13}
Melting ice cube	-10^{9}
Major-league pitch	10^{9}
Striking typewriter key	10^{5}
Flea hop	10^{0}

The magnification of the low energy densities of some potential power sources such as waves or currents allows the more efficient employment of some of the available power, and such intensification may be valuable, particularly if only simple static installations are required. The power of currents can be concentrated in ways involving static structures that will be described later, but sea waves are particularly amenable to such increases in energy density. Indeed, such intensification takes place naturally in numerous coastal sites through refraction, bore interaction, or both processes in sequence.

Refraction of waves in moderately deep water is a nearly linear process, analogous to the refraction of light or sound, and occurs through the agency of current or depth. Bore interaction is a nonlinear process roughly analogous to shock-wave interaction as in Mach-stem formation, where the reflected branch of a shock wave captures the incident branch. An advancing bore in a surf zone will "capture" another wave or bore (even one propagating in a somewhat different direction) whenever the two together can propagate more rapidly (because of the increased amplitude of the combined disturbances) than either can separately.

Both of these concentrating mechanisms can, in principle, be brought into play sequentially to intensify wave energy, and they require only static installations. Where the direction of wave approach is relatively constant, as in the trade winds, these installations could be of a simple design, such as a lenticular hump on the sea floor, one or more wavelengths in extent, with a focus at its center [as in "Arthur's Island" (*7*) and Lockheed's Dam-Atoll] or near shore. It could be produced by dredging or dumping. More sophisticated designs would be necessary for waves of different periods coming from different directions.

The nonlinear concentrator would consist of a number of smooth walls converging toward the focus of the lens. This sort of concentrator has been envisaged (*8*), but perhaps improperly. The purpose of the walls is to reflect a wave in such a way that the incident part captures the reflected part. Thus, in deeper water and before the amplitude has increased due to capture, the angle of incidence must be small, otherwise the wave is scattered without benefit. Further on, the angle of incidence can be greatly increased. Thus the funnel's rate of convergence increases toward the focus, rather than the reverse that is usually proposed.

The wave form is utilized in the bell buoy and in Salter's Duck (Fig. 3) (*9*). The latter is a sophisticated idea, in which the British government is investing considerable research and development effort. In principle, in a regular idealized wave train, Salter's rotor can utilize wave energy with considerable efficiency—both passing and reflecting very little of the incident energy. It remains to be determined whether the Salter Duck is practical in installations exposed to real waves on open coasts. Real waves are ordinarily complex in spectrum and direction, as well as variable in length of crest and amplitude over both brief and long periods of time. They also are almost always associated with tidal variations of sea level, which complicate the design of wave power generators. We will need to give short shrift to many other approaches to wave power extraction. Two, however, deserve attention, namely phase-linked systems, because of their intriguing scaling laws, and anisotropic drag devices, because of their simplicity.

Many wave power approaches, both power producing and power dissipating (such as breakwaters), depend on dimensions of the system that scale as area. However, a body immersed in a wave field is subjected to body forces from the pressure gradient, which scale as volume. Thus, a system utilizing body forces, transferred from the model basin to the field, or from a bay or lake environment to the open sea, scales as the cube of the critical linear dimensions, rather than the less favorable fourth or higher power for appropriate performance that applies for many other systems (*10*).

The pressure field acting on such a submerged body moves at the phase velocity of the wave train, and a body subjected to such a traveling pressure field will ordinarily merely be subjected to oscillating body forces. Curiously, however, a body given an initial velocity in the direction of wave travel can become entrained in the pressure field and, if appropriately streamlined, will move through the water at phase velocity, which in deep water is $14/\pi$ or more times the orbital velocity. This relationship and the associated advantageous scaling law comprise the basis for a modern wave-dissipating system, the dynamic breakwater (*10*). The dynamic breakwater depends on the "non-Archimedean" behavior of immersed buoyant bodies on long tethers. Such bodies experience volume forces that accelerate them into high-velocity, retrograde oscillations with respect to the wave orbits.

In one approach to power generation by this effect, omnidirectional Savonius rotors (*11*) are combined with elements of a dynamic breakwater. The power available from the motion of such elements greatly exceeds that from a rigidly held generator (*12*). However, it is probably difficult to design a system to utilize the full potential of the phenomenon of entrainment at phase velocity for a power-generating system linked to the variable waves of the real ocean.

One other use of wave power, the anisotropic tow line, is worth mentioning. A line a few wavelengths long is fitted with a series of bodies having different drag coefficients to flow in the two axial directions. If such a line is extended with some tension against or in the direction of wave travel, increasing tension will develop down the line, especially when the system is tapered so that both the line and the attached devices increase in size toward the following end. The leading end can be carried by a small boat or even a swimmer. Depending on its length, the dimensions of the anisotropic bodies, and the wave height, such a line can develop high tensions. A small model, 90 meters long with 15-centimeter articulated "umbrellas" every 2 meters and in a moderate surf zone, developed a steady pull of 95 kilograms toward the sea from a 5-kilogram pull exerted by a paddler on a surfboard at its seaward end (*13*). Larger models of such an emergency device should allow a small power boat to tow a large disabled yacht or fishing boat out of danger of stranding on a lee shore. The principle of anisotropic drag could be employed for barge trans-

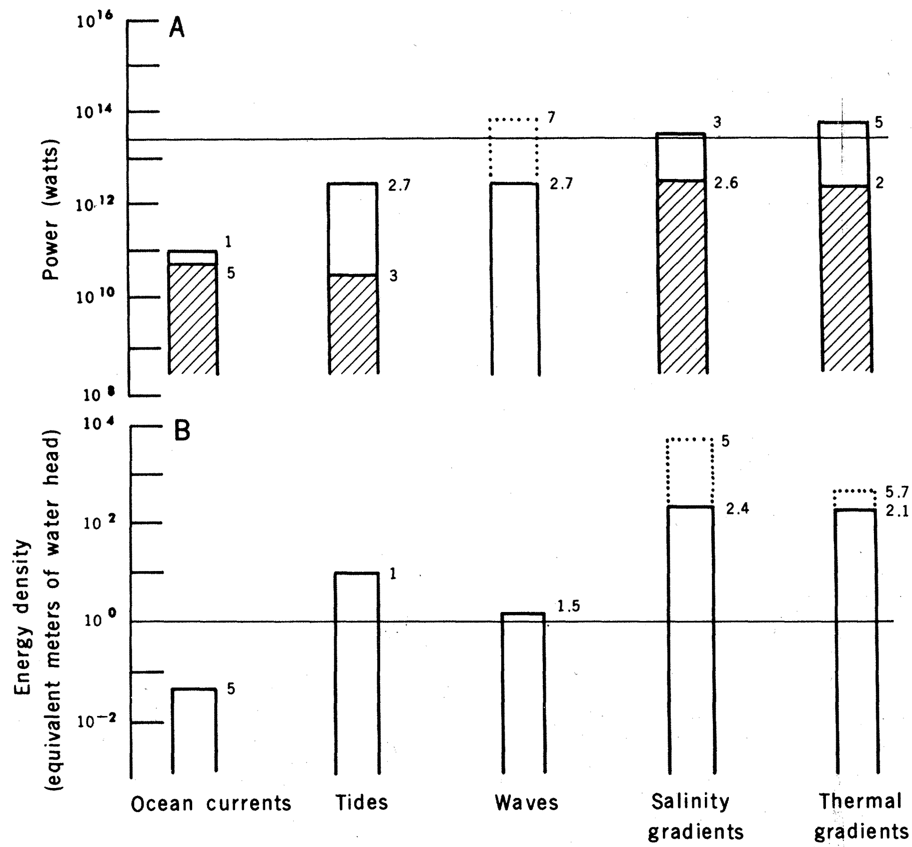


Fig. 1. (A) Power or energy flux for ocean energy. On the "ocean currents" bar, the shading represents the power contained in concentrated currents such as the Gulf Stream. Estimated feasible tidal power is also shaded. The dotted extension on "waves" indicates that wind waves are regenerated as they are cropped. "Salinity gradients" includes all gradients in the ocean; the large ones at river mouths are shown by shading. Not shown is the undoubtedly large power that would result if salt deposits were worked against freshwater or seawater. On "thermal gradients," the shading indicates the unavoidable Carnot-cycle efficiency. The horizontal line at 30×10^{12} watts is a projected global electricity consumption for the year 2000. (B) Intensity or concentration of energy expressed as equivalent head of water. "Ocean currents" shows the velocity head of major currents. For tides, the average head of favorable sites is given. For waves, the head represents a spatial and temporal average. The salinity-gradients head is for freshwater versus seawater, the dotted extension for freshwater versus brine (concentrated solution). The thermal-gradients head is for 12°C; that for 20°C is dotted; both include the Carnot efficiency. [From Wick and Schmitt (*22*)]

port of inexpensive cargoes over some chosen routes, or could generate power if it were applied to a continuous belt running between fixed pylons.

Finally, one characteristic of equilibrium wind waves in the open sea must be mentioned. If substantial quantities of power are removed, energy subsequently flows from the wind to the waves more rapidly than in the equilibrium sea, quickly restoring the removed wave energy.

Tidal Power

The much longer-period surface waves, the tides, are essentially our only discernible entrée to the "fossil" kinetic energy of the earth-moon system, excepting perhaps the "tethered satellite" for space launching and retrieval (*14*). The day lengthening of 1.5 milliseconds per century from tidal friction represents a power loss of about 3×10^6 megawatts. The total rotational energy of the earth is about 6×10^{15} MW-years (*15*). Hence, if all electrical energy needs in the early 21st century (some 3×10^7 MW) could be continuously "mined" from the earth's rotation at 50 percent efficiency, the lengthening of the day would increase 20-fold to 30 milliseconds per century; the radius of the moon's orbit would also increase. The increased length of day of about 5 minutes per million years might be tolerated for the foreseeable future.

Approaches to direct utilization of tidal energy are almost wholly restricted to shallow water, although power generation from tidal pressure in deep water is not impossible. The interrelated effects, which in principle or in fact can be employed for tidal power generation, are vertical displacement, currents, pressure effects, and impoundment. Of these, impoundment is the most commonly discussed and the only case being substantially developed, while currents may provide the simplest approach.

Nearshore areas with a great tidal range and potential for tidal power development are widely distributed and include the coasts of Alaska and British Columbia, the Gulf of California, the Bay of Biscay, the White Sea, the central Indian Ocean, and the coasts of Maine and eastern Canada. Existing installations are in the French Rance River estuary (Fig. 4) and at Kislaya Bay in the Soviet Union.

An important question in evaluating the potential of tidal power is the level of general, regional, or local resonance involved in areas where extreme tidal ranges occur. It was long thought that the broad tidal general resonance Q of the planet—roughly, the ratio of energy within the tidal system to the rate of energy input per cycle—was of the order of unity. Thus any significant increase in tidal dissipation, such as that due to power generation, would have little effect on the general tidal amplitudes. It now appears that the Q of the world's tides is probably more than an order of magnitude greater than unity (*16*). Regional and local magnifications of tidal amplitudes may be the result of further resonances, and the apparent flux of tidal energy in an area of very high tidal range may be merely a visible recycling of the energy in a resonant reservoir. A close analogy would be the kinetic energy in each swing of a clock's pendulum as compared to the much smaller actual and extractable input from the clockworks.

The determination of regional and local Q's and of damping is critical to the selection of sites for tidal power generation. In the case of the river Rance it appears that the installation has reduced the tidal range (*17*), and thus the power flux is about 80 percent of that of the undisturbed estuary. In the case of the often replanned Passamaquoddy tidal power plant on the Bay of Fundy, it appears

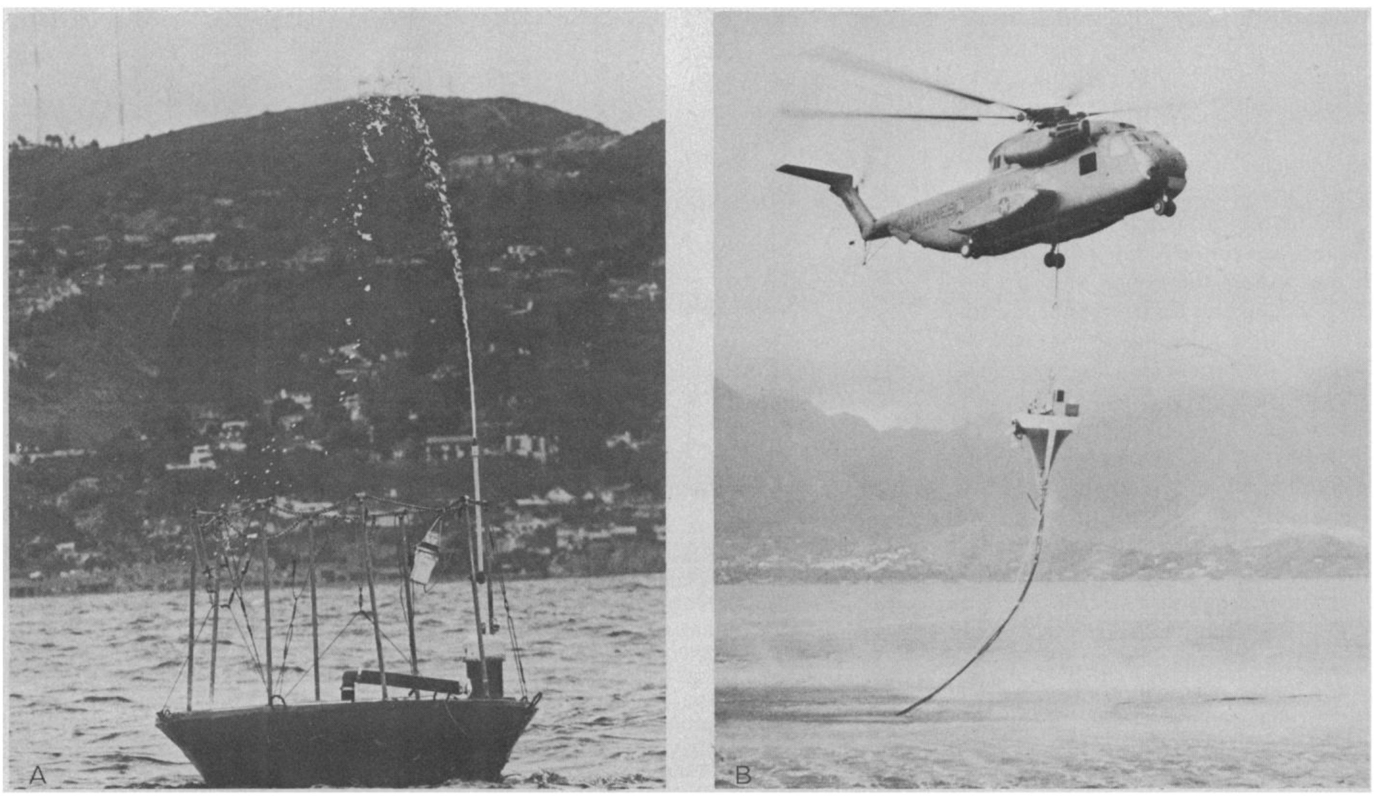


Fig. 2. Wave-pump tests off California and Hawaii. (A) A very small sea in the La Jolla Bight pumps seawater 4 meters high. [Photograph by Steven Suess] (B) A U.S. Marine helicopter assists with the deployment of the wave pump in the Oahu-Molokai Channel. [Photograph from the U.S. Navy]

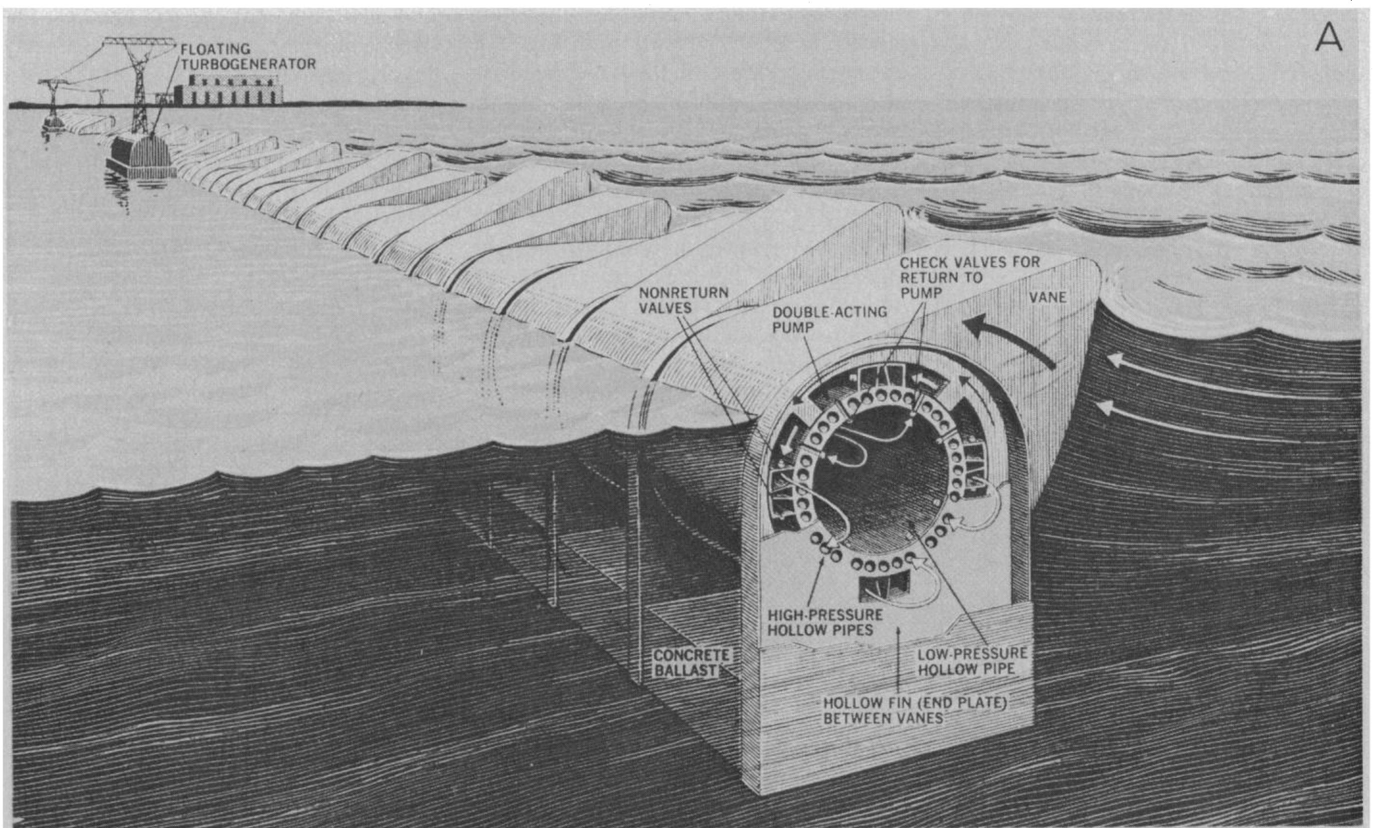
that a carefully designed installation could increase the Q of the system by "fine tuning" and, despite the increased damping, could maintain or even somewhat increase the present tidal range.

There are some advantageous sites between long arms of estuaries or across peninsulas where large phase differences occur in the tides. Such a feature greatly simplifies the impoundment and storage and allows for extended periods of power generation in each tidal cycle. The proposed Golfo San José site at the Valdés Peninsula in Argentina would take advantage of this phase shift (*8*).

Regions where the tidal range is extreme are frequently associated with areas where tidal currents are swift. There may be nodes where the tidal range is modest, as in the central portion of the Gulf of California or in tidal races as in the Seymour Narrows of British Columbia. The concept of dynamic dams may be applicable for power generation in such areas, as described in the following section on currents.

Power from Currents

Great ocean currents sweep the coasts of this planet. Some of the swiftest are in the equatorial regions and along western ocean boundaries. Even these have very low energy densities. Yet there have been a number of proposals for the extraction of useful power from ocean currents (*18*). The installations would, in principle, be relatively simple—turbines, paddle wheels, and the like. Some proposals envisage intensification of the cur-



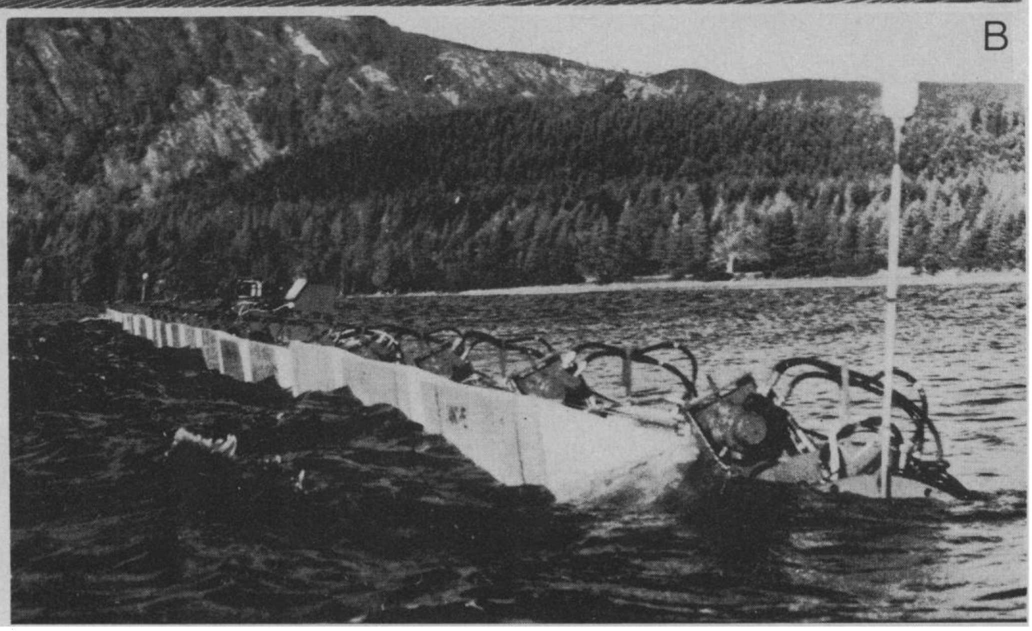


Fig. 3. (A) Salter's Duck consists of a series of segmented cam lobes that are rocked on a large spine by waves, which are shown coming from the right. Pumps connected to the lobes send high-pressure water through small pipes to drive a generator. The back sides of the cams are cylindrical to minimize wave regeneration by the device. [Reprinted from *Popular Science* (*46*) with permission; copyright notice 1975 Times-Mirror Magazine, Inc.] (B) Photograph showing a 1/10 scale model during tests at Loch Ness in 1977 and 1978. [Reprinted from *Ocean Industry* (*47*) with permission]

rent by use of Venturi-like shrouds (flared tubes constricted in the middle) to increase water velocities in the throat and reduce the dimensions of the turbines. However, in a free stream such as an ocean current the Venturi principle is not as readily applied as in a closed system, for the diverging discharge portions of the shroud must extend for many diameters or the water will be merely displaced around the system. If direct power generation from currents were simple and practical, one would expect it to be the practice now in large rivers. Yet this is not the case, and it has long been considered necessary to alter the gradient of rivers by dams or barrages so that much higher velocities or pressures can be achieved over small spatial intervals.

It may be valuable to pursue the general principle of some static structure that concentrates energy in some small part of a very large low-energy flow. Venturi shrouds may be one approach, and there are others. For example, if wind is forced to move through a spiral barrier, a vortex will be generated that will result in a much greater pressure gradient than the mere velocity head. In effect, a large volume of air is made to transfer kinetic energy of rotation to a much smaller volume, and a rather small quantity of air can be allowed to flow at high velocity into the resultant low-pressure region and to interact with turbines of much reduced dimensions at high efficiency (*19*). This configuration is called the dynamic dam. The underlying principle is probably even more applicable to water currents (such as river currents and tidal races) and has been proposed for power generation from such sources (*20*).

Thermal-Gradient Power

Much has been written about marine thermal energy, and bold approaches to its utilization are under way (*21*). It is well understood that the resource is large, but that any substantial utilization would, in effect, constitute mining. The energy is represented by the common thermal gradient in the oceans, which in selected areas is of the order of 20°C between the surface water and depths of 1000 meters or so (*22*). A closed system employing a secondary working fluid (such as anhydrous ammonia) for turbine operation is the common choice, although an open system utilizing the vapor pressure difference of the water is much simpler, since it requires no heat exchangers (*23, 24*) and thus deserves fuller evaluation.

Systems envisaged are huge offshore floating or near-surface structures, pumping deep cold water through a rigid or turgid pipe (stiffened by net internal pressure) extending vertically to depth. Plants would supply the generated power to shoreside grids through submarine power cables, or produce energy-intensive products or fuels (nitrogenous fertilizers, hydrogen, sodium hydride, and so on).

Problems with ocean thermal energy conversion (OTEC) include the design and stability of the intake pipe; biofouling of pipes, heat exchange surfaces, and structure; construction, control, and maintenance of heat exchangers of unprecedented dimensions and required efficiency; corrosion; power transmission; and environmental effects. The best approach to these problems will probably involve testing modules of the final assembly both ashore and afloat where conditions are appropriate. This appears to be the course that the U.S. Department of Energy has chosen in its planned development of OTEC.

Biomass Power

The oceans of the world fix 10^{10} or more tons of carbon per year into organic material, mainly through photosynthesis by microscopic plants, the phytoplankton. A small amount of this production is carried out in shallow water

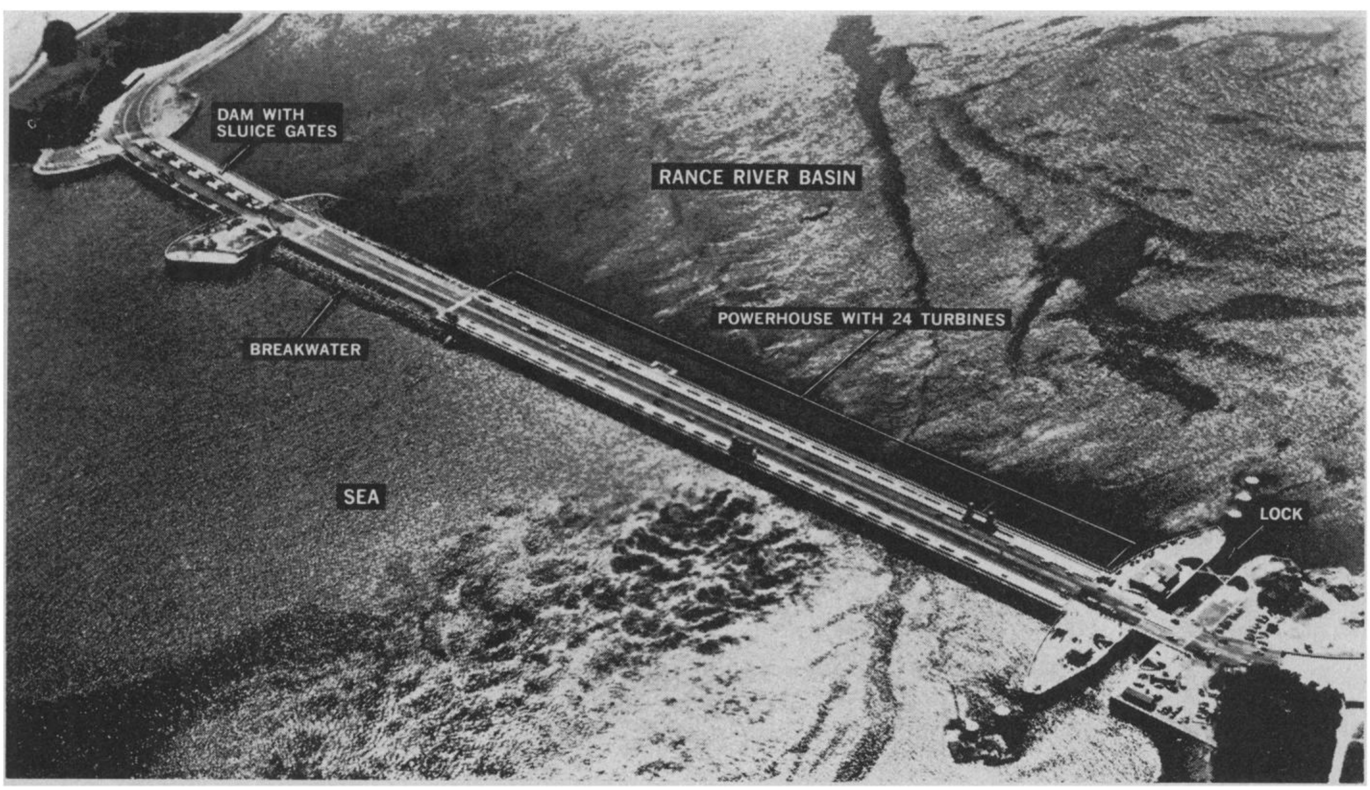


Fig. 4. Tidal-power plant at the Rance River, Brittany. The 8.5-m mean tides vary from 3.5-m neap tides to 13.5-m equinoctial spring tides. Each 10-MW turbine generates power on both ebb and flood flow and can pump water in each direction for a subsequent greater working head. Turbine diameter is 5.35 m. Net output has increased to more than 500 GWh through fine-tuning of operations. [Reprinted from *Popular Science* (*46*, p. 71) with permission; copyright notice 1975 Times-Mirror Magazine, Inc.]

through the agency of large plants such as eelgrasses and kelps, and some of these marine plants are rather efficient producers of organic material and are easily harvested. It has been suggested that kelp farms be developed for the production of so-called biomass energy (*25*). Except for details of its chemistry and its water content, such a crop would differ in no essential respect from other energy crops proposed to be grown on land or from waste organic materials from a wide range of sources. The significance of the biomass approach may depend on its ultimate ability to produce liquid fuels as a substitute for petroleum products. Methane, methanol, and ethanol are now readily obtainable from organic sources. Although methanol is not very energetic, its production appears economically feasible (*26*) and its employment as a liquid fuel is probable. If chemical or fermentation processes can also be developed that efficiently and directly convert biomass crops or waste organics into higher alcohols or other high-energy liquid fuels, biomass energy, including a contribution by marine plants, may make greater additions to liquid fuel supplies.

Salinity-Gradient Power

The salinity gradient is a curiously inconspicuous and only recently recognized potential power source of large total magnitude (*27*). Its energy density is closely measured by the osmotic pressure difference between two solutions. Thus, the salinity-energy density of a river with respect to the sea is equivalent to the energy density of a 240-meter dam. Seawater with respect to a coastal brine pond is equivalent to a dam 3500 meters high. In terms of power, freshwater or seawater flowing into brine at the rate of 1 cubic meter per second releases energy at the rate of 30 MW (*28*). One reason for the inconspicuousness of this source is that common salt (NaCl) solutions release very little energy of dilution in the form of heat; instead, the energy is converted into increasing disorder, or entropy. Nevertheless, it appears that salt domes in coastal regions, which are common traps for petroleum, have two or three orders of magnitude more energy in the form of latent salinity power than in the oil they might contain (*29*).

The following approaches have been suggested for obtaining power from salinity gradients (*27*): (i) vapor exchange between two solutions (preferably at an elevated temperature), called inverse vapor compression; (ii) simple osmotic exchange against a hydrostatic pressure, which is referred to as pressure-retarded osmosis; and (iii) the dialytic battery, which can be thought of as inverse electrodialysis. Only the first of these approaches does not require membranes, with their attendant expense, relatively short life, polarization problems, and high pumping costs. Another membraneless approach has been suggested that may be feasible in arctic regions. Seawater or brine at a temperature below the freezing point of freshwater is employed to freeze freshwater in pressure vessels. The high pressure resulting from the expansion is employed to produce power (*30*). In addition, any of the various schemes for desalination of seawater that have received attention in the last two decades and that are fundamentally reversible are potential processes for the extraction of energy by salination.

Where large rivers flow into the sea, salinity-gradient energy is renewable and its utilization at very low efficiencies is defensible—in the Congo, for instance, the full power released in dilution is about 10^5 MW.

Although salinity energy is a very large potential source, ranking in both total magnitude and energy density well above other sources except chemical and nuclear fuels, it is not certain that it can be practical. We do not know what fundamental constraints limit the efficiency of its utilization or what energy extraction processes are most promising. A new analysis of the nature of electrolytic solutions and the potential for power generation from this immense source is needed. The outlook at present is moderately encouraging. Efficiencies of power extraction of the order of 60 percent with power fluxes of the order of 7 W/m^2 across copper heat exchange surfaces have been obtained in a small inverse vapor compression model, and it appears that there is no fundamental limitation on the efficiency of power extraction (*31*) such as exists in the use of thermal machines.

Miscellaneous Marine Power Sources

Submarine geothermal springs or geothermal aquifers may be important coastal, shelf, or ridge power sources. Several undersea geothermal springs have recently been described (*32, 33*) and many more may await discovery. They have been principally discovered in areas of relatively neutral water density (such as the eastern Mediterranean) or at shallow depths above stable layers (such as Hawaii). Here, their diluted effluent invariably reaches the surface, where detection is likely. It is probable that most submarine springs debouch within or below the stable layers, where their effluents become trapped below the thermocline by the density structure. This trapping would occur for even very large springs—witness the great subthermocline sewage discharges (essentially freshwater springs) that are commonly trapped below the surface. Special technology may thus be required to detect these trapped lenses. A remote conductivity-anomaly detection system that can rapidly survey large areas to considerable depth from the surface has recently been developed (*34*).

The more intense concentrations of geothermal heat—submarine or island volcanoes—are, of course, potential sources of great power. They are extremely energetic, sometimes releasing more than 10^6 MW-years of energy in a single eruption. Some are also possibly the most dangerous objects on earth (outside of nuclear weapons), and one explosive event has been suspected of having destroyed all sea-level culture in the eastern Mediterranean (Santorin, ≃ 1500 B.C). Any substantial power production from such volcanoes might well "defuse" these potentially immensely destructive entities. The predetonation stage of quiescent volcanoes may be typified by a solution of superheated water in a deep magmatic mass (*35*). If so, these objects may be particularly suitable for advanced development of geothermal energy.

About 75 percent of the world's freshwater is in the form of ice—some 2×10^{16} tons. This ice represents a latent heat of −80 calories per gram with respect to water at the freezing point and is a sink for heat about 1.5 percent as energetic as petroleum. If large quantities of ice or icebergs are ever transported to arid regions to supply freshwater, a major problem will be to melt them (*36*). The most straightforward approach will probably be to employ the ice as a heat sink for nuclear, fossil fuel, or OTEC-type power generation.

In addition, however, ice at 0°C can be partly melted by the application of pressure of some 2000 atmospheres with an energy input of about 2.5 cal/g. The resultant slurry of about 30 percent water has a temperature of about −22°C and a residual latent heat capacity of about 50 cal/g without an increase in temperature. Thus, in a tropical sea a temperature gradient of about 45°C can be achieved. Even in a nearly isothermal environment of, say, seawater at 2°C and pressurized ice, a temperature gradient of 24°C is obtainable; this would provide a coolant with a heat capacity four times that of the OTEC process. Of course, this approach requires high-pressure heat exchangers and may be impractical in a large installation. However, it is provocative to note that when two phases of a substance are present in a nearly isothermal environment, rather high temperature gradients and potential power can be achieved with small energy inputs, by a change in phase of one form.

Direct Employment of Marine Power

Many arid desert coasts of the world are associated with strong equatorward coastal currents. Where these coasts are steep, very cold water from depths is ordinarily brought near the shore. Such a sink for heat (the OTEC coolant) can be employed for the production of freshwater by direct condensation from the atmosphere and for the air conditioning of very large complexes. If the electrical energy required to air-condition a single unit by conventional methods is instead devoted to pumping up deep cold seawater and forcing it through a spray chamber in a driven flow of air, it is calculated that more than 2000 units can be air-conditioned for the same power input. A small test model of such a system showed a multiplication factor of 500 over conventional air conditioning (*37*). If the heat exchange is carried out to a freshwater charge that cools the air in spray chambers, freshwater is produced from atmospheric moisture as a by-product.

Much fuel is employed to maintain harbor channels, yet the tidal currents are capable of transporting many times the quantity of sediment annually dredged in these channels. Two new approaches have been developed to guide the tidal transport processes in desirable directions. One of these employs a bottom-mounted sediment fluidizer that suspends sediment at the appropriate tidal stage so that the sediment is transported in planned directions (*38*). The second approach is based on the discovery that most tidal estuaries operate in regimens where sediment transport (τ) increases with the nth power of mean stream velocity (V), where n is a very high exponent. That is, $\tau \sim V^n$, where $n > 5$, ordinarily. Thus, a superimposed flow equal to a small fraction of the tidal flow added to ebb tide and subtracted from flood tide can disproportionately increase net sediment transport out of an estuary. This water could be pumped from the sea into an estuary, allowed to flow by tidal gradients through flumes fitted with tide gates, or added and subtracted from the flow by programming a tide gate in a tidal arm of the estuary (Fig. 5) (*39*).

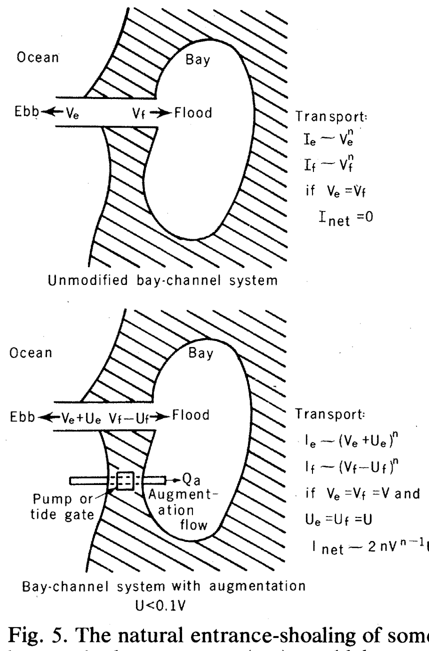


Fig. 5. The natural entrance-shoaling of some bay or harbor systems (top) could be controlled by tide flow augmentation (bottom). A small enhancement of ebb flow and diminution of flood flow results in a highly disproportionate net sand transport I_{net} seaward, with $n > 5$ ordinarily. Here V_e is the transport velocity on ebb; V_f, transport velocity on flood; U_e, incremental velocity on ebb; U_f, incremental velocity on flood; and Q_a, augmentation flow rate.

There are many other possibilities. For example, in the "inverse electrodialysis" approach to salinity energy, the internal electrical currents can be utilized for electrolytic processing. Also, if some of the otherwise high-salinity cells are connected instead to the low-salinity cells, that water is desalinated (*40*).

Marine-Associated Factors in Power Production

Two major aspects of the role of the ocean in power production are the use of seawater for cooling fossil- and nuclear-fired power plants, and the use of the ocean as a site for the disposal of high-level nuclear wastes. These may ultimately become the ocean's most important contributions to man's energy supplies.

The slow broad rivers of deep cold water, originating mainly in high southern latitudes, constitute an immense heat sink (the T_2 in the efficiency equation) that underlies all oceans and deeply communicating seas. The existence of this sink is the basis for OTEC proposals, but this water will probably find greater use as a coolant for conventional and nuclear power plants located on steep coasts. Its low temperature will compensate, at least in part, for the increased length of intake pipes, because the flow rates can be reduced. Furthermore, it is probably much less stimulating than surface water to organisms that foul condenser surfaces, and it may even be toxic to the fouling organisms because of the uncomplexed metallic ions it contains. In addition, such very cold water could be discharged at temperatures much closer to that of ambient surface water, greatly reducing environmental stresses associated with coolant discharges.

Such deep water contains high levels of inorganic plant nutrients, and the metals it contains are apparently rapidly chelated in mixing with surface water. It has been estimated that use of deep seawater as a coolant would stimulate up to 31 times the minimum per capita needs for animal protein for each per capita unit of electrical power production on open coasts, and up to 2500 times if the effluent could be confined in a lagoon or bay (*41*). Thus, ancillary benefits of near-ambient discharge, reduction of fouling and pumping costs, and stimulation of productivity might ensue from the choice of deep water as a coolant for coastal power plants.

The controversial question of the means of disposal of high-level radioactive wastes has been extensively discussed (*42*). The problem involves providing certainty over periods of time that are extremely great. Recently, through the elucidation of plate tectonics, man has developed unprecedented understanding of the broad geophysical and geological behavior of the planet. Insight into this behavior may extend further into the future in the case of the deep ocean basins than other areas of the earth's crust. The technology now exists for drilling through the deep sedimentary layers of the ocean basins, and appropriately stabilized high-level radioactive wastes could be implanted 1000 m below the basin sediments under 6000 m or more of water.

Much more must be understood concerning diffusion of ions, conduction of heat, and so on before any final determination can be made, but there are many advantages to subseabed disposal. First is the degree of certainty concerning the future behavior of ocean basins over such immense periods of time. In addition, the pressures are far above the critical pressure of water, and expanding steam cannot form. Gas generation becomes relatively unimportant. Risks of fissuring and contamination of fresh groundwater are nonexistent. A most important advantage is the relative invulnerability of the sea to radioisotopes, which stems from its chemistry and that of its living creatures. For example, ^{129}I, which has a half-life of 20 million years, is thought by some to be a particularly serious problem of long-term disposal and to fix the time scale of concern (*43*). But at sea ^{129}I would be diluted by stable isotopes of iodine, which are present in abundance. Any biological or chemical mechanism that could concentrate the conceivable levels of ^{129}I at sea to dangerous levels of radioactivity would produce a far more hazardous toxic concentration of normal iodine. Similar irreversible isotopic dilution processes pertain to other long-lived fission products that might be disposed of below the seabed and to short-lived radioisotopes (*44*). They may also apply to the transuranic actinides, although they are of less fundamental concern because their levels in wastes can be made very low.

Conclusions

Ocean waves, tides, currents, salinity gradients, and temperature gradients (including ice) are five natural forms of energy that have a potential for yielding useful power. Each has its own geographic distribution, natural flux, reservoir, energy density, concentration, and range of possible approaches.

Only the natural fluxes of salinity and temperature gradients could provide energy in excess of the estimated 21st-century levels of electric power consumption. However, the flux of energy from winds into waves would increase with extensive use of wave power, and hence wave power also falls into the substantial category.

The temperature-gradient energy alone is present in a reservoir that is many times its annual flux and hence may be utilized in a "mining" mode, as can salinity-gradient energy from salt domes or salt deposits. Tidal power is the most widely distributed form, but not necessarily in useful sites, and ocean-current power is probably the most narrowly distributed. Expressed in terms of an equivalent head of water, energy densities range from some 200 m for salinity gradients (rivers to sea) and thermal gradients through 10 and 1.5 m for tides and waves to several centimeters for currents. Simple static structures can concentrate some of these dilute energy forms.

The complexity of practical devices for the extraction of power appears to trend with energy density, the salinity gradient requiring the most complex approaches and currents the simplest (*45*). Waves and tides are now being employed to produce power. It is probable that all of these forms will contribute to regional power grids or to the manufacture of energy-intensive products in the future. Waves, tides, and currents may easily supply modest power—for example, for remote stations, buoys, and islands.

Marine-related power sources are perhaps more important. High-temperature submarine geothermal springs may be common and utilizable at high efficiencies. Island and submarine volcanoes have the potential for advanced conversion. An iceberg from the Antarctic, transported to and melted for water off tropical desert coasts, should yield thousands of megawatt-years of energy through a process similar to the proposed OTEC system. A single coastal salt dome represents 10^4 to 10^5 MW-years of salinity-gradient energy—hundreds of times the fuel energy from a dome-associated petroleum field.

Any of these forms of energy can be utilized for purposes other than electrical-grid input or energy-intensive products. Salinity-gradient power can be employed internally to desalinate brackish water; thermal-gradient power can produce freshwater with power or air-conditioning as a by-product; tidal flow can be guided to dredge harbor channels; waves can be employed directly for propulsion (as, of course, can winds and currents).

The understanding gained in developing these sources will have important applications. For example, temperature-gradient systems may lead to an effective "bottoming" cycle for the cleanup of thermal waste from conventional power plants, and salinity-gradient systems will require an advance in our understanding of colligative (molar) properties of aqueous solutions.

Perhaps the most important relationship of the ocean to human power needs in the future will be in the employment of seawater for heat rejection and of the deep region below the sea floor for the disposal of nuclear wastes.

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