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Power, Fresh Water, and Food from Cold, Deep Sea Water

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The sun's radiation is both the essential requirement of all life and the great source of man's energy. Besides keeping us warm, it supplies, directly or indirectly, (i) most of the energy we use, (ii) all of our food through photosynthesis in plants and many links of the food chains, and (iii) our fresh water supply from the cycle of evaporation from the sea, to clouds, to rain, to rivers.

The oceans contain 98 percent of the earth's water, over 1.3 thousand million cubic kilometers of that other great necessity of all life. With 71 percent of the earth's area, the oceans receive most of the sun's radiation to the earth. This radiation is absorbed on the hundreds of millions of square kilometers of the oceans and stored in vast amounts of living organisms stemming from photosynthesis and in the remains of this life—as organic and inorganic nutrients—and as vast amounts of heat in the surface waters of the tropic seas. These two resources —heat to supply energy and nutrients for food chains from single cells through all edible plants and animals up to man—are our greatest resources, as yet practically untapped. In the utilization of the heat, the third product, also from the usual radiation from the sun, fresh water, may be produced, often where needed most.

Sea water is always cold in the deeps, and often it approaches the temperature of its maximum density, near the freezing point. It is cooled in the Arctic and Antarctic where it settles to the depths and, by a grand thermosyphon system, moves on the bottom toward the tropics, where it is warmed, and moves again in tremendous currents toward the poles, to recycle. Photosynthesis in the upper layer penetrated by the sun produces single-cell organisms, thence bigger marine growths, and, by steps, up to the earth's largest plants and animals. Surface waters in the tropics may be crystal clear because photosynthesis has utilized all nutrients; and larger living things have consumed all of the small organisms which cause haze, and thus have stripped the water of carbon, nitrogen, and phosphorus, the principal nutrients for life.

But this life, largely in surface water, dies, as does that in deeper water; and the remains settling slowly, as befits a burial, return to "dust," that of the ocean depths. Slowly these remains disintegrate; and, in solution and as particles, residues are carried in the deep currents back to particular areas of upwelling—only about 0.1 percent of the total area of the oceans. Here the great amount of nutrients causes an explosion of marine life. Just one major one, the upwelling of the Humboldt Current off Peru, supplies one-fifth of the world's total fish harvest.

Availability of Thermal Energy

Again with reference to energy (here heat), its concept implies the temperature of the "hot" substance being higher than that of another "cold" substance. Heat is only usable by its transfer to a colder body. Deep sea water may be from 15° to 25°C colder than surface water; but there is little conduction of heat, top to bottom, and little mixing because of density differences, except in notable upwellings.

While this temperature difference between surface and deep waters is small, considering usual sources of energy, the available heat is the product of this difference multiplied by the available masses of sea water which are infinite for all practical purposes. Means for the conversion of this available heat to electrical energy would give continuously very much more than mankind has found capability to use.

For example, the Gulf Stream, first studied scientifically by Benjamin Franklin, carries the heat absorbed in the Caribbean and the Gulf of Mexico past the coast of Florida. Some 2200 cubic kilometers of water per day may be as much as 25°C warmer than the cold, deep water which it was. To heat just 1 cubic kilometer of sea water per day 25°C would take six or eight times as much energy as all of the electrical energy produced in the United States. The reverse is staggering; it has been estimated that this heat in all of the Gulf Stream, if discharged to water colder by 25°C, could generate more than 75 times the entire electric power produced in all of the United States (*1*).

Both coasts of Africa, the west coast of both Americas, and the coasts of many islands, particularly in the Caribbean area, have places within a few miles of land where sea water has a surface temperature of 25° to 30°C, while at 750 to 1000 meters below the surface, the temperature may be 4° to 7°C (*2*). In some places, the ocean floor drops off from the shore line very steeply to an ocean deep within some hundreds of meters of land. The ideal location for a land-based power plant, using warm surface water on one side of a peninsula, would have a great sea depth close to shore on the other side of the peninsula. The contour of the bottom should be favorable to the installation of a large suction pipe to supply cold water.

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Potential Values

Both this energy and these nutrients are available, and they could supply all the world's power, light, and much of the protein food it uses; but so far they are locked away from us by the difficulty of their recovery from such dilute sources, compared to the relative ease of the utilization of other, more concentrated resources. With shortages of energy and food in the world, this utilization is a job for the present, and one well within the capabilities of technology now available. The dilution is indeed not prohibitive. The water brought up from the depths of tropical seas will absorb surface heat energy equal to the mechanical energy available from a 120-meter waterfall. Compared to other systems proposed for using solar energy, this utilizes a vast reservoir at any one of many places. Always the equipment for utilizing solar energy is large and expensive. And the mariculture using the nutrients can produce $125,000 of product per year from each hectare of land converted to ponds [$50,000 annually per acre].

Thus, if very large amounts of cold, deep sea water can be brought to the surface, warmed in receiving the heat discharged by a suitable power station, and passed to tropical ponds wherein its nutrients are used in photo- and biosynthesis by marine plant and animal food chains, the ultimate product is not fish meal or an artificial substance, but choice shellfish. The water is warmed in the pools to a temperature higher than surface sea water and is passed to the high temperature side of the power cycle. The simplest is direct production of very low pressure steam, turbine-generation of electricity, and condensation of the steam in warming the cold, deep sea water, giving fresh water as condensate.

Power Cycle and Process Engineering

Great minds backed by large sums of money, somewhat less large when the potential benefits are considered, have worked throughout almost a century to develop systems of utilizing the small difference of temperatures of surface and deep sea water to produce power (*3*). Claude made the most optimistic contributions 40 years ago (*4*), and the great problems which he recognized were principally two—the installation of the enormous pipeline to carry water from the depths and the removal of air from the evaporating warm water (*5*).

However, theoretically mechanical energy—and from it electrical energy—can be developed from heat from any body at any temperature being passed to any other body which can receive it, because of its lower temperature. Such energy is always more difficult and less efficient to produce, the lower this temperature difference is. Carnot showed the maximum efficiency to be $(T_1 - T_2)/T_1$ where T_1 is the temperature of the hot body and T_2 is the temperature of the cold body. These are measured above absolute zero.

This temperature difference for efficient heat engines may be many hundred or even a thousand degrees. The closer the temperature of the heat input approaches that of the output, the less the efficiency becomes. Here warm water is at 30°C and it is cooled, in producing very low pressure steam, to 25°C, the temperature of the steam. If this steam is condensed at 15°C by heating cold water from 5° to 10°C, with a 5°C loss in the condenser tubes, this temperature of 15°C may be regarded as the low temperature at which all heat is discharged.

Hence, if the steam supply is at 25°C, or $273° + 25° = 298°K$, above absolute zero, and the corresponding temperature of the heat rejection is 15°C, or $273° + 15° = 288°K$, then the maximum thermodynamic efficiency is $(298 - 288)/298$, or about 3.3 percent. Practically, because of many energy requirements in related machinery, and because of many losses, the efficiency obtainable could not be more than about 2 to 2.5 percent. Of equal importance usually, the amount and cost of equipment required always *increases* greatly with a decrease of the temperature difference. Thus, the heat in a cubic kilometer of warm sea water may be passed to colder sea water to develop mechanical energy, then electrical power. Necessarily, the heat available at this low temperature can be converted to power only with a large, costly plant, at a very low efficiency, and by the handling of extremely large amounts of the cold sea water to absorb the heat. However, the total amount of water to be handled may be less than the amount of water required to produce the same amount of power in a hydroelectric plant. Dams, penstocks, and machinery of a hydroelectric plant are also expensive in developing a "free kilowatt"; that is, free of cost of energy.

The cold water does not have to be lifted from the great depth by the pump; only the friction head must be considered, plus the small static head caused by the difference in density of the cold water and the average density of the water from the surface to the bottom of the pipe.

Various designs for floating power plants have been made with vertical suction pipes suspended from the vessel and with submerged power cables and fresh water lines carrying the products to the shore. However, these would make controlled mariculture more difficult.

Any plant for handling these large volumes of water and converting the available thermal energy to mechanical and then to electrical energy will be huge and expensive; and even the smallest one which would be worthwhile for demonstration purposes will involve many millions of dollars worth of equipment.

The simplest of many possible systems that have been studied depends on flash evaporating, in an evacuated chamber, a small amount of the warm water as it is partially cooled. This gives a maximum of 1 percent of the weight of the water as a very low pressure steam. This low pressure steam turns a turbine in cooling further and then is condensed on tubes through which the cold water from the deep is passing and being warmed. The condensate is fresh (distilled) water, almost always a valuable commodity on tropical coasts; and its sale adds to the revenue from the power produced by the generator turned by the steam turbine.

Because of the very low temperature and pressure of the steam, the turbine must be specially designed; and the condenser must be large. Some systems have not provided a surface condenser, but have depended on "open" condensation by sprays of the cold sea water. This produces no condensate fresh water, the sale of which is a valuable revenue for any system, unless a cooled fresh water spray were used (*6*).

A substantial plant using low pressure steam with a condenser for fresh water has been engineered (*7*). Several other designs were studied and discarded. The design for a 7180-kilowatt (net) power plant also showed an output of 6 million U.S. gallons of fresh water per day at a total installed cost of $18.4 million.

Several factors were considered in the economic analysis; and charts were made to show the interrelation of (i) the capacity factor, that is, actual production compared to maximum capacity, and (ii) the cost of power generation. Thus, for an investment of $18.4 million, a calculated maintenance and operating cost of $100,000 per year, at an assumed fixed cost of capital of 12 percent per year and a capacity factor of 0.9, fresh water would be produced for $1 per 1000 U.S. gallons, and electric power for 6 U.S. mills per kilowatt-hour; and, in general, total costs can be divided between the two products as desired, since total amounts of both are produced.

As another example, if the capital or fixed charges are taken as 16 percent per year at a capacity factor of 0.90; and if the cost of producing power is taken as 6 mills per kilowatt-hour, fresh water costs are $1.38 per 1000 gallons, or if power cost is taken as 1 cent per kilowatt-hour, then fresh water is $1.26 per 1000 gallons.

Under the economic conditions prevailing at the particular site, which changed during the program, the rate of return on private risk capital was not regarded as sufficiently attractive to private investors to warrant this investment to compete with power and fresh water from a combustion plant. The warm water was regarded as the more valuable stream—it contained the heat that was discharged to the equally necessary stream of cold water, brought up by the very expensive pipeline and pumping system.

In the case of a mariculture program, the valuable stream is that from the depths, with the nutrients therein. The warm water stream does nothing for the mariculture, except that its vapors condense and heat the cold water somewhat in passing through the condenser, and the higher temperature increases the rate of growth of marine life. However, it should be noted that, in passing through the sun-heated enclosed basins for mariculture, the effluent, when it is discharged back to the sea, may be warmer than the surface water from the open sea. If so, this effluent would be cycled through the flash evaporator or boiler of the electric power–fresh water system, and only one stream would be drawn from the sea. The process engineering, mechanical engineering design, and civil engineering design were completed along with the economic analysis which showed that this project was economically profitable. However, under other particular conditions pertaining at the site, it would be desirable to delay the construction of the plant for fresh water and electric power production. Some details may be of interest.

Plant Layout and Equipment as First Designed

Because of an existing highway at the proposed site, the power and desalinating units were laid out about 140 feet from the shore line. Hydraulic losses and steam friction losses were minimized by short conduits with a minimum of bends. The warm surface water intake, a large subsurface conduit, supplies the boilers through trash racks and fine screen, then deaerators. Special design adapted from desalination evaporator practice minimized losses during flash-boiling of about 1 percent of the warm water supplied. A boiler discharge pump removes the cooled surface sea water.

A turbine with horizontal rotor is directly above each boiler and was designed to operate at a low speed because of its large diameter.

The two pipes for cold sea water intake were designed with a nominal diameter of 4.13 meters and to withstand the stresses imposed by the carefully planned system of installation and by the irregular sea bottom, the contour of which was explored from a small submarine. The section was located 4100 meters offshore at a depth of 975 meters.

Improvements in Design of Plant and Equipment

Improvements have been made in the newer design planned for installation as an integrated component with the mariculture unit at a demonstration plant. Various improvements and advantages will be included in the new design.

1) The water effluent from mariculture operations will be used, and it will be warmer than open sea water, thus a better efficiency should be achieved. Also there will be a considerable economy in almost eliminating the warm surface sea water circuit.

2) A greater ratio of surface water to deep sea water will use the latter more efficiently.

3) Improved design of the hydraulics of deep water systems should reduce installation and power costs.

4) Condenser cost will be greatly reduced if plastic tubes are used.

5) Boilers will use the controlled flash evaporation (CFE) system to reduce losses in pressure and temperature drops which will increase production of both water and power (*6, 8*). The CFE system also will reduce substantially the deaeration costs, which require 20 percent of power produced in previous plants.

6) In some locations where fresh water is unusually expensive, all of the available heat will be used for this production, with no power.

Mariculture in Cold, Deep Sea Water

Deep sea water which has absorbed the heat from warm surface water in producing power and fresh water has been brought to a temperature more favorable for biologic growth. It is rich in nutrients which often are exhausted almost completely by the high rate of photosynthesis in the sparkling clear surface tropic waters; and is practically free of organisms which produce disease in humans, predators and parasites of shellfish, fouling organisms, and man-made pollutants. By contrast, shellfish culture has had major pollution disasters in the past years along the continental Atlantic coast.

An experimental station has been operated on the north coast of St. Croix, one of the U.S. Virgin Islands, near Puerto Rico. Here the ocean floor slopes sharply to the Virgin Islands Basin (4000 meters deep) and reaches a depth of 1000 meters, 1500 meters offshore. Three [69-millimeter inside diameter (3 inches nominal)] polyethylene pipe lines, each 1800 meters (6000 feet) long, supply water from a 870-meter (2900 feet) depth in an amount of 159 liters (42 U.S. gallons) per minute. This water is warmed in being drawn up through the small pipes so that its cooling effect would be negligible but it is satisfactory for the mariculture work.

This water in January 1973 averaged (microgram atoms per liter) nitrate nitrogen, 32.1; nitrite nitrogen, 0.13; ammonia nitrogen, 1.1; phosphate phosphorus, 2.15; and silicon in silicates, 21.7. The salinity was 34,841 parts per million. While these amounts equal only a relatively small weight of synthetic nutrients which could be added, this clean, unpolluted water is free of parasites and hostile microorganisms which could endanger the cultured animals, or remain in their bodies to be passed to humans. Also the water, if used in a power and desalination cycle must be pumped up to gain its cooling value. It may also be fortified with additional amounts of added nutrients having components carefully chosen to give the greatest value in the particular mariculture used.

A development program is now in progress to determine the most desirable plant and animal species for a food chain to give optimum value of the produce species at the top of the chain with minimum cost in production. Two varieties of diatoms have been particularly satisfactory; and after inoculation the water develops up to 1 million diatoms per milliliter, when it is metered into the shellfish tanks.

Early work showed a 27-fold increase in unicellular algae (diatom) grown in water from a depth of 800 meters compared to that from the surface; and peak yields of 230 grams per cubic meter (1900 pounds per 1 million U.S. gallons) have been obtained. This amounts to 2.8 grams of algal protein per cubic meter of water.

Various types of shellfish feed on these unicellular animals by filtering them from the water they continually process; from previous work it appeared possible to obtain at least a 60 percent conversion of the diatoms to commercial foods. Thus, from an overall material balance, these nutrients of the deep sea water, basically the nitrogen, which would be utilized through the food chain to be explained, should give 1 kilogram of fresh clam meat per 300 cubic meters of deep sea water (27 pounds per 1 million gallons).

From the available marine life in nature, the most promising species are being chosen; there are hopes of improving the natural strains, as has been done by animal husbandry in every animal which has ever been bred for food. Greatly improved yields appear through proper control of (i) natural nutrient concentration—and possibly that of artificial nutrients, or other additives; (ii) solar radiation—by adjusting the depth of the ponds; (iii) water temperature; and (iv) still other variables as these first or axiomatic ones are optimized.

Algal Cultures

Many species of microscopic algae have been isolated, cultured, and studied as cultivated food for shellfish. Those preferred are fast-growing strains, readily accepted by shellfish and causing their rapid growth; they should be hardy against competitive organisms, against high summer temperatures, 32° to 33°C of the pools, and against the excessive sunlight radiation which prevails in shallow pools. Some have developed weight increases of young oysters (3 millimeters) of more than 75 percent in 3 weeks.

Extensive experiments in all sizes of tanks and pools up to 45 cubic meters (12,000 gallons) of 1.2 meters (40 inches) depth, with many variables, have indicated that dependable production of large amounts of algae satisfactory for shellfish food can be maintained. This work to improve the breed and production of algae continues because of the promise of considerable improvements in the development of better, more stable, and hardier strains. Also the geometry of the pools is being optimized; and continuous operation has been developed.

Shellfish

Oysters and clams from cultures stemming from Long Island (New York), Japan, and various tropical locations have been worked with as brood stock and for growth studies.

Experimentation with the shellfish has indicated that certain species grow very rapidly indeed in this "artificial upwelling" system: thus, hybrid clams were grown to market size in 6 months. Similarly, the European oyster and the bay scallop were grown from spat to market size in 6 months (*9*). This is considerably faster than generally occurs in nature. Clams, European oysters, and bay scallops of commercial size grown in this system were submitted to a panel of seafood experts for taste testing, and judged to be of excellent taste and superior to those harvested in natural waters. Thus, hybrid clams averaging 8 grams, on introduction, increased in weight almost five times to 38.5 grams in 6 months so they could be marketed in the littleneck size.

Scallops multiplied their weight 60 times in 145 days, from an average single weight of 0.24 gram at an age of 8 days to 14.42 grams. Average lengths of the scallops were, respectively, 9 and 40.7 millimeters.

Oysters have grown from 3 millimeters to market size in a little more than 8 months; and one species of oysters grew from an average live weight of 1 gram when introduced to 70 grams in 74 days.

Shellfish filter the microorganisms from the water for food; their filtering efficiencies for gathering and retaining the food cells from the pools have varied from 49 percent without culling of the shellfish to over 90 percent when the small shellfish have been periodically harvested to stimulate the growth of the larger ones remaining. These harvesting techniques are now being optimized.

Crustaceans

A great variation in the growth rates of shellfish has been observed; one long-term objective is to improve the strain by selective breeding of the fastest growing individuals, which also have other desirable characteristics. Thus a large number of small clams at different ages would always be culled to minimize competition of the faster growing animals; and the culls may be used as a very acceptable food for crustaceans. First tried were adult spiny lobsters, native to St. Croix in the Virgin Islands. The best of these showed an average weight gain (in an 89-day period between moltings) of 55 percent, while eating 5.2 times as much food weight as its gain in weight.

Similar experiments are under way with cold water lobsters from the Massachusetts coast which are growing at a greatly accelerated rate in the warm waters of the mariculture ponds.

Seaweed

If the effluent from the shellfish and lobster growing operation were returned directly to the sea, the animal wastes might constitute a source of pollution. Therefore, experiments are under way with commercially useful seaweeds which can be processed to obtain either agar or carrageen. These seaweeds are grown in the effluent from the animal tanks, to optimize the nutrient utilization in the system, and to purify the discharged waters before returning them to the sea.

Chain of Nutrient Utilization

The water from the deep will have been substantially warmed in the plant for production of energy and fresh water; and the optimum utilization of its nutrients appears now to be via (i) single cell algae; (ii) filter-feeding shellfish, such as oysters and clams, which feed on the algae; (iii) lobsters, shrimp, and possibly other crustaceans which feed on culls of the shellfish; and (iv) specialized seaweed, which grows in effluent water containing the solubilized body wastes of the shellfish and crustacea, and has several important markets.

Mariculture Ponds and Operation

The mariculture will be done in a series of shallow concrete pools of optimized depth. The deep sea water flows through slowly to permit residence times, not widely different, for (i) algal growth, (ii) shellfish growth, (iii) crustacean growth, and (iv) seaweed growth. The apportionment of the time periods for the different growths has not been established exactly to date but will be optimized insofar as possible to give the greatest financial return with the minimum of land and pool area.

For the demonstration plant now being planned, it is expected that 25,000 gallons (95 cubic meters) of deep sea water per minute will be available and that there may be a total of 6 hectares (15 acres) of ponds required with a total time of water in transit of about 2 days. This area may be divided approximately as follows: (i) 50 percent for algal growth, (ii) 10 percent for shellfish growth, (iii) 10 percent for crustacea growth, (iv) 20 percent for seaweed growth. It is impossible as yet to estimate the optimum operational yields of different products; but it is expected that, at an average annual yield, an average value at the plant will be about 340,000 pounds of shellfish at $2.25 to $2.50 per pound of meat. This works out to be an average of over $50,000 annual revenue per acre of ponds without credit for values that cannot yet be optimized.

For a larger plant, handling 870,000 gallons (3390 cubic meters) per minute, a somewhat lower unit price for shellfish may have to be taken; and the total annual revenue has been projected to be between $20 and $25 million.

Summary

Many times more solar heat energy accumulates in the vast volume of warm tropic seas than that produced by all of our power plants. The looming energy crisis causes a renewal of interest in utilizing this stored solar heat to give, in addition to electric power, vast quantities of fresh water. Warm surface water, when evaporated, generates steam, to power a turbine, then fresh water when the steam is condensed by the cold water.

A great increase in revenues over that from power and fresh water is shown by a substantial mariculture pilot plant. Deep sea water contains large quantities of nutrients. These feed algae which feed shellfish, ultimately shrimps and lobsters, in shallow ponds. Wastes grow seaweed of value; and combined revenues from desalination, power generation, and mariculture will give substantial profit.

References and Notes

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4. G. Claude was developing support in the United States in 1925–26 for the pilot plant which he then built in Cuba. He gave a demonstration lecture in the laboratories of the University of Michigan where D. F. Othmer was then a graduate assistant. Claude's equipment included a small tank for warm water and one for cold, a vessel to which the warm water was admitted to undergo flash evaporation (about 1 percent), a small steam turbine driven by the low pressure steam that was forming, a condenser having the cold water in direct contact with the turbine exhaust steam, and a vacuum pump for air removal. A small generator was driven by the turbine and was wired to a small electric bulb, which lit as the house lights went off—and the audience cheered.
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7. The sea water power and fresh water plant was engineered by Alemco, Inc., now a division of Viatech, Inc., Syosset, New York. One of us (D.F.O.) is a consulting engineer to and director of both corporations. The plant was designed for another island site in the Caribbean which was then regarded as eminently suitable.
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10. Supported by Sea Grant 1-36119. This article is Lamont-Doherty Geological Observatory contribution No. 2016 and City University of New York Institute of Oceanography contribution No. 21. The first engineering design was made by Alemco, Inc., a subsidary of Viatech, both of Syosset, New York.