

Solar sea power

Heat engines operating in the tropical oceans, capitalizing on the temperature differential between upper and lower levels, could provide a source of economical, pollution-free electricity

Clarence Zener

The French physicist Jacques D'Arsonval¹ predicted in 1881 that Man would someday mine the ocean for heat to power his civilization, rather than mine the earth for fossil fuels. Specifically, he suggested that a heat engine operate between the warm upper layer and the cold deep water of the tropical oceans. The power delivered from such a heat engine may appropriately be called "solar sea power," for the sun would rapidly restore to the upper layer the heat transferred to the cold deep water.

Because solar sea power is essentially pollution-free, and is renewable, it has special relevance today. If D'Arsonval's prediction is to become a reality, solar sea power must, however, pass the acid test of economic feasibility. The story I tell here has led me to the personal conclusion that the probability of economic feasibility is so high that advanced reactors, such as the liquid-metal fast-breeder reactors (LMFBR) the Atomic Energy Commission is developing, will be economically obsolete before development is completed.

In contrast to solar sea power, where the ocean acts as the solar collector, power plants that require man-made solar collectors appear distinctly uneconomic. For example, Aden and Marjorie Meinel estimate that their desert solar power plant² will cost several times an atomic power plant³, for the same output.

Physical description

The heat engine of a solar sea power plant would be similar in principle to

standard heat engines. The sketch on the opposite page gives an impression of how such a plant might appear, and figure 1 shows the essential features.

The working medium can be any fluid with a reasonably high vapor pressure at ambient temperature, and with good heat-transfer characteristics. D'Arsonval suggested ammonia, among other fluids. More recently developed refrigerating fluids, such as a freon, might be preferable. In figure 1 we have assumed ammonia merely for illustrative purposes. A reasonably high vapor pressure is necessary to avoid unreasonably large turbines. The economic failure of Georges Claude's attempt^{4,5} to develop solar sea power is probably due⁶ to his using the very low vapor pressure of sea water itself to drive his turbine.

The quantity of warm water that must pass through the boiler is, of course, enormous. But so also is the quantity of water that passes through a modern hydroelectric plant. In order to acquire a physical feeling for this quantity of water, let us calculate the work developed by the heat given up by one gram of warm sea water as it passes through the boiler. According to the example of figure 1, this heat is 2 calories, and our Carnot efficiency is 0.033. Our ideal work is 2.8×10^6 ergs. This is just the ideal energy that a gram of water delivers to a hydroelectric power plant with a head of 93 feet. The quantity of warm water that passes through the boiler is thus comparable, on the basis of power output, to the water passing through a typical hydroelectric plant.

Most of my physics friends point to the boiler as the Achilles heel of the solar power system. The thermal effi-

ciency of the system is less than one-tenth that of a conventional modern fossil-fuel plant. For the same power output the heat exchanger within the boiler must thus transfer more than ten times as much heat. Therefore, they conclude, the heat exchangers must cost at least ten times more in our system than in a conventional fossil-fueled plant. The fallacy to this argument is that the boiler tubes in a conventional power plant operate under the doubly adverse conditions of high internal pressure and high temperature. The high pressure requires thick walls, the high temperature requires still thicker walls or more expensive material. In contrast, our boiler operates at only a very low pressure difference, and at ambient pressure.

The entire solar sea plant will be neutrally buoyant, submerged at such a depth that the vapor pressure of the working fluid will be largely compensated by the sea water's hydrostatic pressure. Thus, corresponding to the vapor pressure for ammonia of 105 lbs/in² at 15 deg C, the appropriate submergence depth would be approximately 200 feet.

The various components may, of course, be arranged in a variety of ways. Hilbert and James Anderson⁶ have suggested an arrangement to minimize the pressure difference external and internal to both the boiler and condenser. Thus, the higher pressure within the boiler requires it to be below the condenser. I have suggested a modular design⁷ to minimize manufacturing cost. Here the boiler, condenser and engine modules are all of the same standard size, say 8 ft $\times$ 8 ft $\times$ 40 ft, such as could be transported

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conveniently by truck, train or boat.

The tropical oceans provide an especially favorable site for solar sea power both because of their constant warm upper surface layer and because of the relatively shallow depth of the cold water. Figure 2 illustrates⁸ a typical temperature profile in the tropical ocean.

Power economics in the mid-1960's

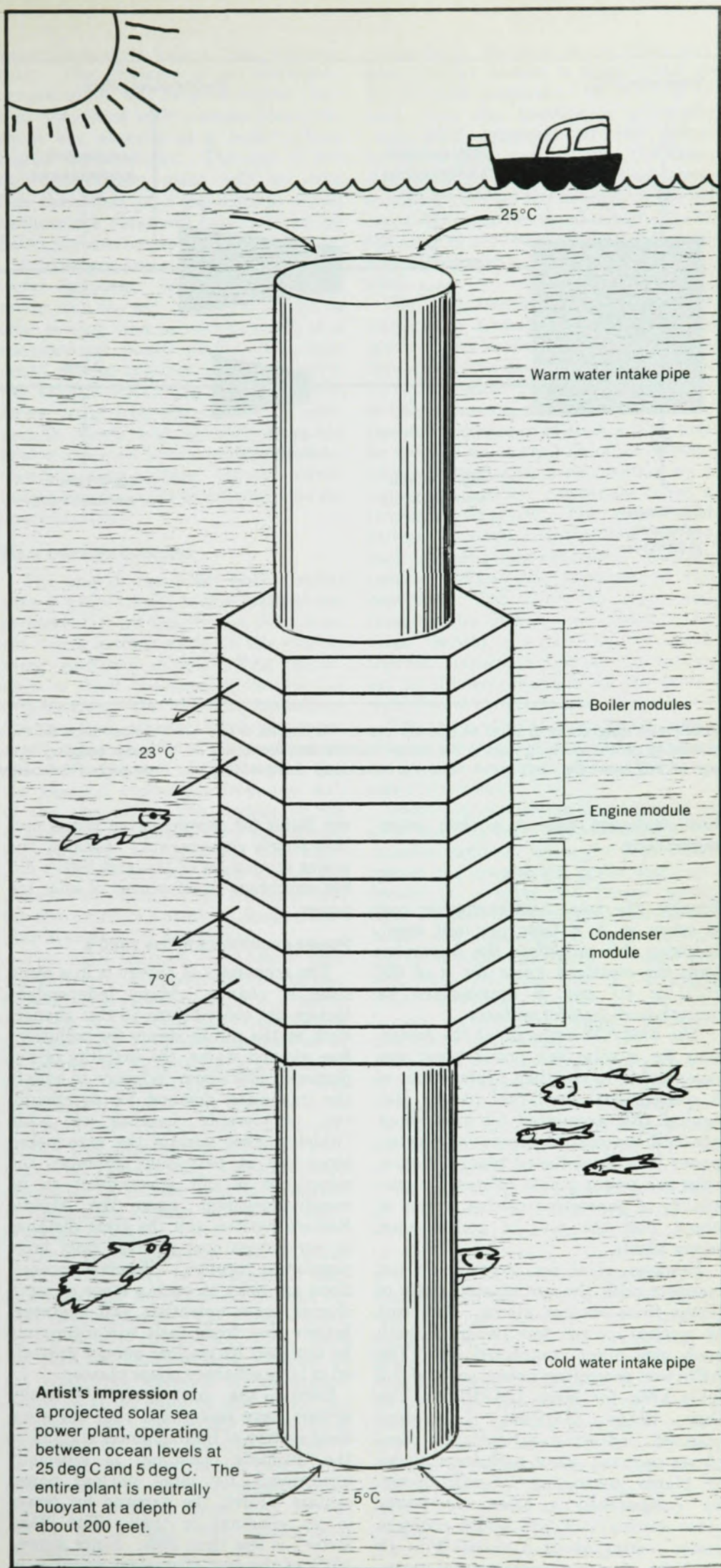
Solar-sea-power plants have not attracted the attention of physicists probably because their operation does not require sophisticated physics—only sophisticated plumbing. But this very simplicity renders them amenable to cost estimation.

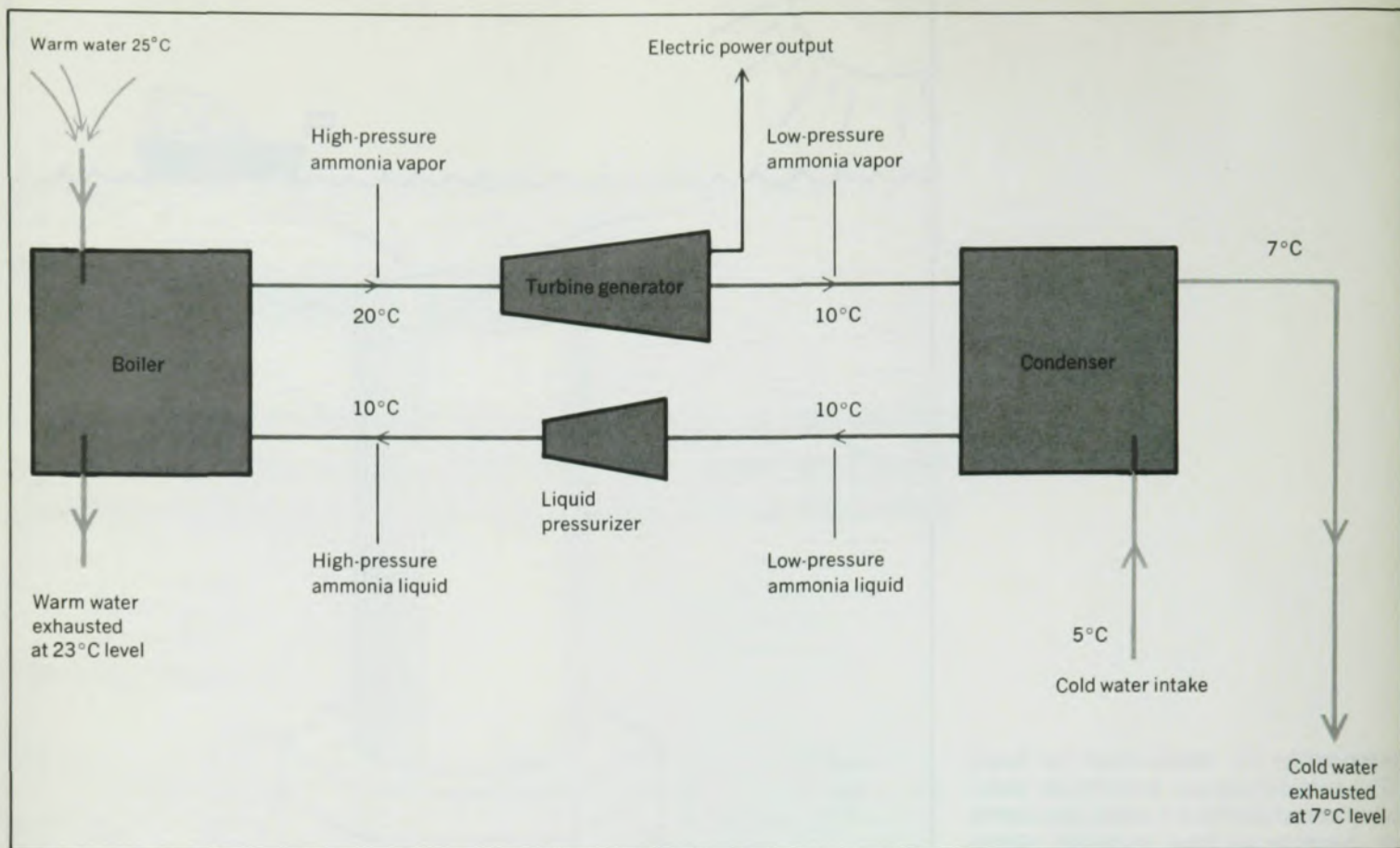
A detailed cost estimation⁶ was carried out in 1966 by the Anderson father-and-son team. (J. Hilbert Anderson, by the way, was at that time a student at MIT; James H. Anderson, his father, is a consulting engineer.) Their estimate of \$165 per kW can best be summarized as

$$\begin{aligned} \text{Total cost} &= 1.6 [(\text{cost of boiler and condenser}) \\ &+ (\text{cost of other components})] \end{aligned} \quad (1)$$

This formula conforms to the standard procedure of first calculating component costs, and then adding 60% to account for assembly costs, engineering, and so on. Half the total component cost is for the boiler and condenser. To provide an appropriate background for the latter part of my story, I shall sketch how the boiler and condenser costs are arrived at.

From the required power and the known efficiency, the total heat flux Q is computed. From the heat-transfer coefficient h and the total temperature drop across the heat exchanger δT , the





Schematic diagram of a solar sea power plant. Ammonia is assumed to be the working fluid in the boiler, turbine and compressor in this example, but more recently developed refrigerating

fluids, such as the freons, might be preferable. The quantity of water passing through the boiler is comparable with that passing through a hydroelectric plant with the same output. Figure 1

heat exchange area A is then determined from

$$Q = h \delta T A. \quad (2)$$

Finally, the total heat-exchanger cost is taken as $A \times$ (cost per unit area). In using this procedure the Andersons took the standard value for h of 600 BTU/hr ft² deg F appropriate for smooth heat-transfer surfaces.

The \$165/kW estimate of the Andersons for a solar sea power plant was comparable to the then average cost of a conventional fossil-fuel plant. But capital cost accounted for only about one-half the cost of generating electric power in a fossil-fueled plant. Hence, solar sea power plants offered the possibility of generating electric power at about half the cost of conventional power plants.

However, solar sea power could not compete with the anticipated costs of power from nuclear plants. The cost of nuclear power was declining with each new plant contracted for. The AEC was projecting power costs of 1.5 mills/kWh for large LMFBR's. The Oak Ridge National Laboratory planned industrial-agricultural complexes centered about such large nuclear plants generating 1.5-mill power. By comparison, a solar sea power plant costing \$165/kW would generate power costing about 3 mills/kWh. (2×10^{-5} is an appropriate capital recov-

ery factor for converting an initial cost into hourly repayments.) Clearly, the power economics of the mid-1960's did not encourage development of solar sea power.

Power economics in the 1980's

The economics of energy is in a rapid state of change. Many independent factors are contributing to this change, such as the public desire for pollution-free air and water, the inability of our domestic petroleum industry to satisfy the increasing demand for petroleum, our unfavorable balance of trade (which cannot sustain the anticipated large rise in petroleum imports), the reluctance of our government to be energy-dependent upon the Middle Eastern nations and the great distance of our largest coal reserves from large population centers. Whereas predictions are risky in such a stage of rapid change, most scientists and engineers believe that fossil fuels will ultimately be replaced by nuclear energy generated in large off-shore power plants.

During the past year,⁹⁻²³ many writers have recognized that our standard system of linking power stations to the ultimate consumer is especially uneconomic for large nuclear power centers. First, the demand for power is not constant in time. The "load factor" is less than 50%. Since almost 100% of the cost of nuclear power is in

the initial cost of the plant, a 50% load factor doubles the cost of power. Second, the cost of transmitting and distributing electrical power is as great as the cost of generation, and will be several times greater if the public persists in demanding underground distribution. These two difficulties are simultaneously removed if the electric power is used to electrolyze sea water at the plant site, and the resulting hydrogen and oxygen gas is then fed into a pipeline network. Low-cost gas storage is already used, and pipeline transmission and distribution of energy costs only a small fraction of electrical transmission of energy.

An economy in which off-shore generated electric power is used to electrolyze sea water, and the resulting hydrogen and oxygen gas is then piped inland to fuel the economy, is now known as the "hydrogen economy." W. E. Winsche, K. C. Hoffman and F. J. Salzano²¹ have given a detailed analysis of the anticipated low cost of a hydrogen economy over that of an all-electric economy. A diagram of such an economy is given in figure 3, taken from W. Hausz, G. Leeth and C. Meyer's paper.¹⁹ Of particular importance is the suggestion of using hydrogen gas as a vehicular fuel.²⁴⁻²⁹ A number of studies have shown that only minor modifications need be made to a standard internal combustion en-

gine to burn hydrogen. Not only are carbon monoxide and unburnt hydrocarbon absent in the emissions, but nitric-oxide emission is much lower than when gasoline is the fuel. Hydrogen gas was actually used²⁵ as a vehicular fuel in Germany during the late 1930's.

In a hydrogen economy the off-shore nuclear plants must compete with solar sea power plants. Such tropically based plants could electrolyze water at depth, thereby producing hydrogen and oxygen at high pressure. These gases would be fed into submerged tankers, which would then be towed underwater to the appropriate coastal areas.

In such a competition, I believe solar sea plants would win. The 1.5-mill/kWh power predicted by the AEC has proven to be a mirage. Costs of 10-11 mill/kWh are now predicted,³⁰ corresponding to a plant cost of approximately \$400/kW, which is about the cost of off-shore nuclear plants now being contracted for. But \$400/kW is more than two times the 1966 Anderson estimated cost of solar sea power plants. While inflation has occurred since 1966, heat-transfer surfaces have recently been developed that promise to halve the total cost of a sea power plant. I will discuss these improved surfaces in the following section.

On-shore coastal electric power plants fueled by high-pressure hydrogen and high-pressure oxygen from solar sea power plants will have fantastic properties. Conventional fossil fuel plants have either steam turbines or gas turbines. The steam cycle has the advantage that pressurization is performed upon a liquid; hence a large pressure ratio, greater than 400, and hence a high efficiency, can be obtained with a negligible irreversible loss. The disadvantage of a steam turbine is that it must be fed by a boiler, which costs as much as all the other power-plant components combined.³¹ The advantage of a gas cycle is that combustion takes place within the working medium itself, so a boiler is not required. The cost of a gas-turbine plant is therefore low. The disadvantage of a gas cycle is that pressurization is performed upon a gas. Because of the inherent irreversible processes in a continuous-flow gas compressor, the compression ratio is low, less than 20, and hence the efficiency is low. Our coastal electric power plant fueled by high-pressure hydrogen and oxygen gas will have the combined advantages of the steam and gas-turbine plants, with neither of their disadvantages. No boiler is required, because combustion is internal to the heat engine, and hence the cost will be low. No gas compressor is required, because the gas is formed at high pressure deep in the tropical ocean, and hence the efficiency will have the high

value associated with a high pressure ratio. The efficiency of our hydrogen-oxygen plant will be even higher than that associated with a steam plant, because the absence of a boiler allows higher temperatures. The cost of our hydrogen-oxygen plant will be even less than that of a gas-turbine plant, because our plant will have not only no boiler but also no gas compressor.

A hydrogen-oxygen plant emits only water and heat. If the exhaust is directly into the air, it will be similar to that coming from a cooling tower of a conventional power plant. The heat could also be rejected into the adjoining coastal water. In winter the exhaust could feed directly into a community steam heating system, or via heat exchangers into a community hot-water heating system, thereby eliminating the necessity of burning fuel for space heating.

Heat transfer surfaces

The area of the boiler heat transfer area is proportional to the thermal impedance $1/h$ for the flow of heat from the warm surface water to the evaporating ammonia surface. This impedance is itself the sum of two partial impedances: the thermal impedance for the flow of heat from the warm water in the interior of the warm water channel to the wall of the channel, and the thermal impedance from the wall of the channel to the surface of the evaporating ammonia. For the smooth heat-exchange surfaces that were standard in the mid-1960's, the second impedance was much larger than the first for the small temperature drops available in solar sea power plants.

The high thermal impedance from the surface of a smooth wall to the surface of an evaporating fluid is a manifestation of the difficulty of nucleating bubbles. By preparing surfaces so as to contain an abundance of permanent nucleation sites, Union Carbide has been able to lower this impedance to values of only $1/60$ that of smooth surfaces. One preparation method³² consists of introducing almost-closed channels. A second method³³ consists of coating the surface with a thin layer of spongy copper.

The thermal impedance on the water side of the boiler heat-exchanger surface may also be improved through recent developments. The major contribution to this impedance comes from the thin laminar-flow layer adjacent to the wall. An analysis of the experiments of D. F. Dipprey and R. H. Sabersky³⁴, on the effect of surface roughness on both the friction coefficient and the heat-transfer coefficient, shows that the thermal impedance of the water laminar layer may be reduced by a half with appropriate roughening.

Similarly, the area of the condenser heat-transfer surface is proportional to the thermal impedance for the flow of heat from the condensing ammonia vapor-fluid interface to the metal heat-exchanger surface, plus the thermal impedance from the metal heat-exchanger surface to the water in the interior of the condenser channels. As in the case of the boiler, the first impedance dominates under standard conditions.

The high thermal impedance of the condensing ammonia comes from the gradual thickening of the ammonia film as it runs down a smooth surface. L. G. Alexander and H. W. Hoffman³⁵ of ORNL have recently shown that the thermal impedance of such a film may be reduced by at least an order of magnitude by replacing a flat surface by a corrugated surface, commonly called a Gregorig surface.³⁶ The ridges and valleys of such a corrugated surface each perform distinct roles. Surface tension reduces the thickness of the condensed film over the ridge and thickens the film in the valleys. The ridge thereby presents a very small thermal impedance, while the valleys act as efficient channels for the downward flow of the condensed ammonia.

The thermal impedance of the water side of the condenser may be reduced in the same manner as for the water side of the boiler.

From the proceeding discussion it is clear that, by using sophisticated heat-transfer surfaces, we might drastically reduce the cost of the boiler and condenser of a solar sea power plant. But, because the combined cost of the boiler and condenser is only one-half the total component cost, it would appear that the total cost of the plant could be reduced, at most, by one half. Closer investigation shows, however, that this is not the case.

Suppose we have optimized a system to have minimum cost for a fixed performance specification. Suppose further that because of a later technical advance we are able to reduce the cost of one component in the system. In order to take the maximum advantage of the new technical advance, we should re-optimize the entire system. In the re-optimized system the relative cost of the various components remains essentially the same as before the technical advance.^{37,38} Further, suppose the cost of one component is proportional to a single parameter, such as thermal impedance h^{-1} . Then at optimum design the total cost is proportional to this parameter raised to the power δ , where δ represents that fraction of the total cost attributable to this component; we conclude that the total cost of a sea-power plant is roughly proportional to $(h^{-1})^{1/2}$. Thus, if the overall thermal imped-

ance of the boiler and condenser is reduced by a factor 1/9, the overall cost is reduced by the factor 1/3.

Environmental impact

Society will not now allow any large-scale activity without a prior examination of potential environmental effects. It is therefore advisable at this time to estimate the environmental consequences of a large-scale exploitation of solar sea power.

The direct effect of such large-scale exploitation is a lowering of the temperature in the upper warm layer. Let us ask what is the relation between the power extracted and the change in temperature.

In seeking an approximation to this model, we shall assume that in the tropical oceans equilibrium exists between the absorption of solar energy and the loss of heat by vaporization. When we now operate solar sea power plants, heat will be pumped from the warm upper layer to the cold deep water. The temperature will now be

lowered, thereby decreasing the loss of heat by vaporization. A new equilibrium will be established when this reduction in heat loss through vaporization exactly equals the rate of heat removal by the solar sea power plants. If by q we denote the rate at which heat is transferred, per cm^2 , from the warm upper layer to the cold deep water, and if p is the net power extracted per cm^2 by the solar sea-power plants, then

$$q \approx p/0.02 \tag{3}$$

We take the rate of vaporization as proportional to the vapor pressure itself. The above equilibrium assumption then leads to

$$q \approx (C/\pi)(H/RT)(\delta T/T) \tag{4}$$

where C is the solar constant, H is the molar heat of vaporization and δT is the drop in temperature. Elimination of q leads to

$$p \approx 5 \times 10^{-4} \delta T \text{ watts/cm}^2 \text{ deg C} \tag{5}$$

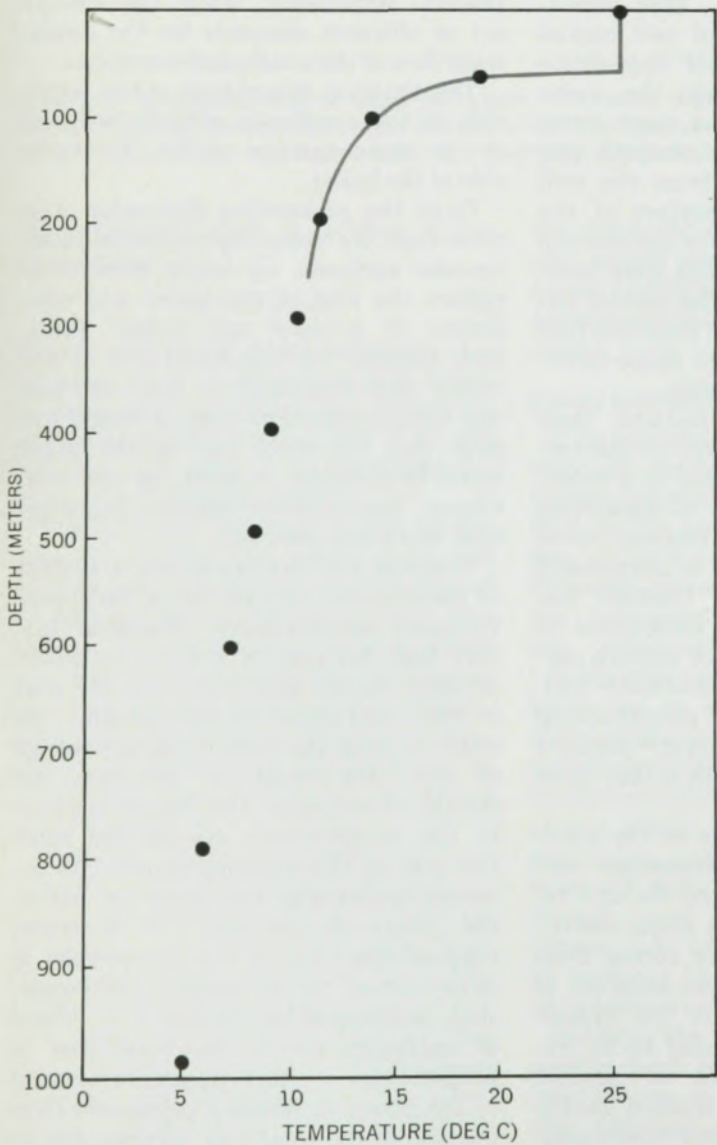
If we now consider that half the earth's

surface between the latitudes 20 deg North and 20 deg South is occupied by tropical oceans suitable for solar sea-power plants, the total power generated will be

$$P \approx 60\delta T \times 10^9 \text{ kilowatts/deg C} \tag{6}$$

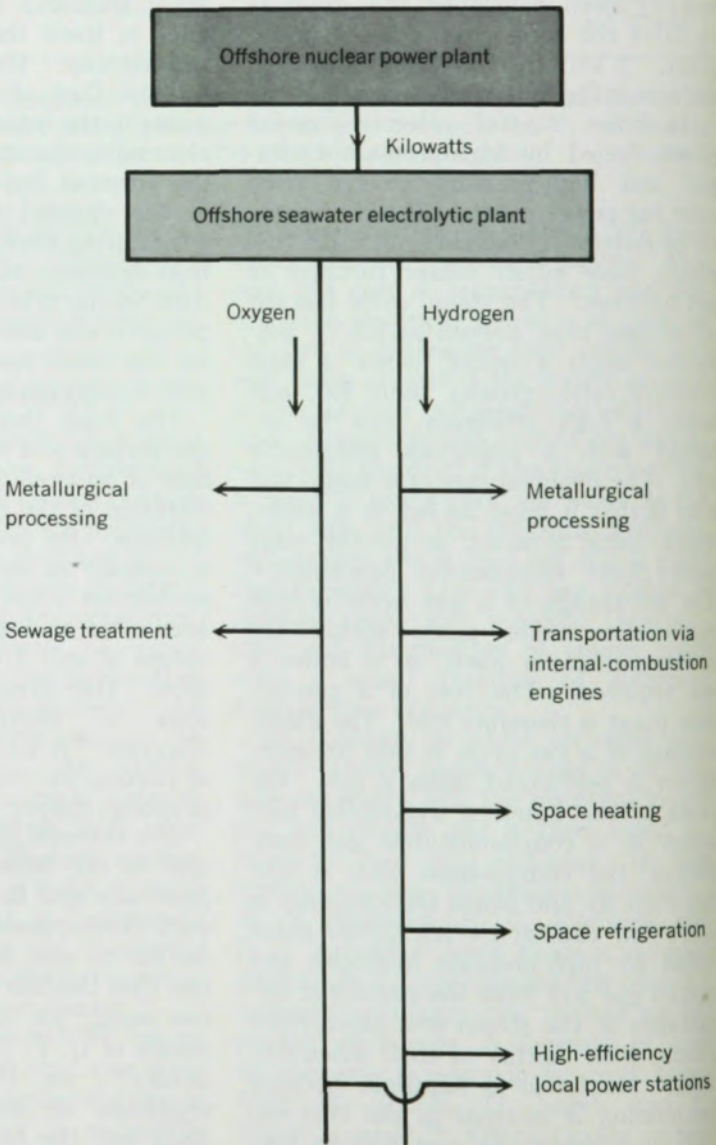
Consider the case where δT is 1 deg C. The power generated is then 60 billion kilowatts. The United Nations projection for the world's population in the year 2000 is 6 billion.³⁹ Now the 1970 US population of about 200 000 000 consumed energy at the rate of 2 billion kilowatts.⁴⁰ We conclude that the tropical oceans in the year 2000 could supply the whole world with energy at a *per capita* rate of consumption equal to the US *per capita* rate in 1970, and suffer only a one-degree C drop in temperature.

Let us now ask what are the qualitative effects of a lowering of the surface temperature of the ocean. The most direct is, of course, a lowering of the tropical atmospheric temperature. A more subtle effect is uncovered when



Typical temperature profile in the tropical ocean, taken from F.C. Fuglister (reference 8, pages 119 and 186). The black dots are readings at 8°22'N, 27°27'W, and the solid curve is a continuous recording at 8°24'N, 27°27'W.

Figure 2



The "hydrogen economy." Electrolytically produced hydrogen and oxygen, from off-shore nuclear or solar sea power plants, could take the place of today's "all-electric" economy. (From W. Hausz, G. Leeth and C. Meyer, reference 19.)

Figure 3

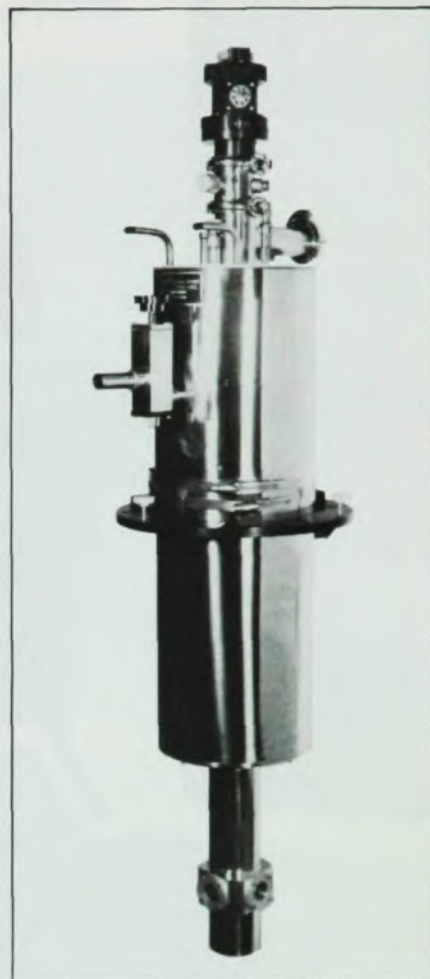
we realize that the lower tropical surface temperature has been caused primarily by a transfer of heat from the surface to the deep layers, rather than by a removal of heat from the ocean. The lowered loss of heat by evaporation and by radiation, the heat input remaining constant, results in a net heat input from the sun. This net tropical heat input must be dissipated outside the tropics, presumably by increased convection currents.

Most people in the world would probably welcome a somewhat warmer ocean outside the tropics. Climatologists in particular will welcome an increased transfer of heat from the tropics to the temperate zone, for they are worried⁴¹ that the present interglacial period may be coming to an abrupt end, and that such an end may be accompanied by a marked drop in mean temperature over a period as short as 100 years!

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