Ocean Thermal Power Plants

G. L. Dugger
H. L. Olsen
W. B. Shippen
E. J. Francis
and
W. H. Avery

Ocean thermal power plants employ the temperature difference between the solar-heated surface layer of the tropical ocean (25 to 27°C) and the water at 700 to 1200 m depth (5°C) as the source and sink for a Rankine cycle system to generate electric power. The fact that the overall thermal efficiency is only 3% means that large quantities of seawater must be pumped, but the resource is tremendous: there are 80 million km^2 of tropical oceans between the 10°N and 10°S latitudes. This energy source is available 24 hours per day, in contrast to direct solar-thermal or earth-based solar-cell (photovoltaic) systems. Many investigators concur that ocean thermal power plants can be built with existing technology, that they would be cost competitive with domestic fossil-fuel and nuclear power plants, and could contribute significantly to our energy needs by 1985 with negligible environmental impact. Since most of the tropical ocean resource is remote from the U.S., the energy must be used to produce needed energy-intensive products such as ammonia (for fertilizers), aluminum, and liquid hydrogen at sea.

Introduction

THE HARNESSING OF SOLAR ENERGY is one of the two possible paths to significant alleviation of our dependence on our dwindling fossil fuel reserves without incurring the hazards posed by a large increase in the number of nuclear fission power plants, for which the fuel supply is also finite. The other path, nuclear fusion, will continue to receive its share of research and development but is not expected to be fully developed until well into the 21st century. Direct solar energy and some of its derivative energy sources (e.g., wood, winds) have contributed greatly to man's needs in the past but have been eclipsed for a time by the exploitation of fossil fuels. Now that we have finally been forced to recognize the limitations of the fossil fuel supplies on "spaceship Earth," we should make a rational, determined effort to find the most practical ways to employ the solar energy with which we are blessed.

Our national space program has developed photovoltaic power via solar cells. Great progress has been made, but solar-cell cost must be reduced 100-fold before land-based photovoltaic power systems will compete with coal-fired and nuclear power plants.[1] Some high-technology enthusiasts are proposing the placement of huge solar collectors in orbit to beam microwave energy to receivers on earth, but that requires another great cost to develop a generation of space transportation systems *beyond* the shuttle to put it there.

More promising for the near term is the use of direct solar-thermal systems for the heating and cooling of buildings, but this application will grow relatively slowly, and it will take care of only a small fraction of our total demand for energy. Direct solar-thermal power plants and biological fuel farms can meet some of our requirements[1] but will occupy significant areas of our increasingly precious habitable land. Wind power systems also can provide some local needs but require structures towering above our landscapes to yield even 1 MW_e each.[1] Both direct solar-thermal and wind systems also are limited to generating power only on an intermittent basis, when the sun shines or the wind blows.

[1] H. J. Killian, G. L. Dugger, and J. Grey, Editors, *Solar Energy for Earth, An AIAA Assessment*, American Institute of Aeronautics and Astronautics, New York, N. Y., Apr. 21, 1975.

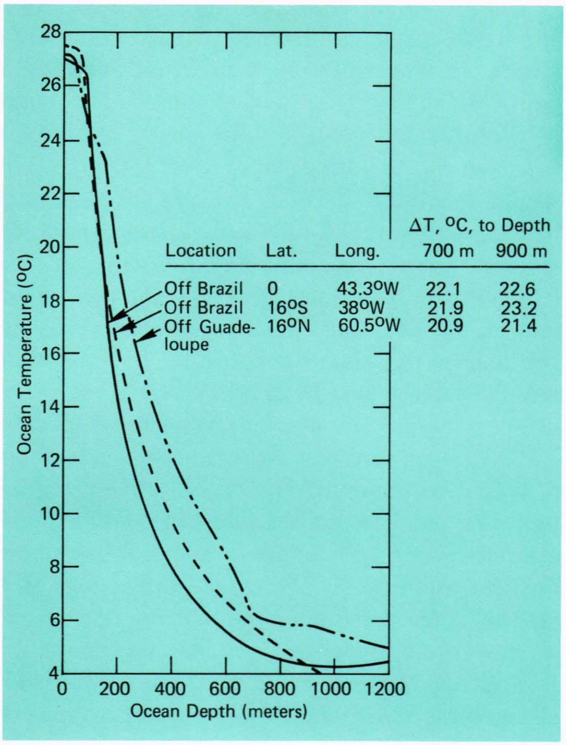

Fig. 1—Temperature profiles in the tropical Atlantic Ocean (from data in Ref. 2).

Oceans cover 71% of the earth's surface and, therefore, receive the majority of the solar energy incident upon our planet. In our tropical oceans, the temperature difference ($\triangle T$) that exists between the surface and the depths (thanks to the deep flow from arctic regions) provides the source and sink needed to operate a heat engine. This $\triangle T$ is available 24 hours a day for power generation. Figure 1 shows some typical temperature profiles derived from previous data.[2] There are 30 million square miles (80 million km^2) of tropical oceans within the $\pm$ 10° latitude band near the equator where $\triangle T$'s of 20 to 24°C exist year round and, except for limited local regions, currents are below 1 knot at all depths and winds do not exceed 25 knots. The vast potential for energy development from this ocean thermal resource can be appreciated by noting that a quantity of electric power equal to the entire projected U.S. demand in the year 2000 (about 7×10^5 MW$_e$) could be obtained by extracting from the oceans in this $\pm$10° latitude band an amount of energy equal to only 0.004% of the incident solar energy.

This paper addresses the bright prospects for practical, near-term implementation of Ocean Thermal Energy Conversion (OTEC) power plants in tropical oceans to generate electric power and use it on board to produce ammonia (for fertilizers), liquid hydrogen, and other energy-intensive products such as aluminum and magnesium. The writers believe that such plants can begin to contribute significantly to our energy needs in the 1980's, in direct economic competition with fossil fuel and nuclear power sources, if given adequate research and development support. No technological or cost breakthroughs are judged to be needed to do this, and no unfavorable ecological impacts are foreseen. To the contrary, one possible large favorable impact could be achieved by making use of the extra nutrients brought up with the cold water to enhance the production of biological farms (mariculture) at sea. The latter subject is beyond the scope of this paper but is being addressed by others.[3,4]

Historical Highlights

Use of an ocean $\triangle T$ to drive a heat engine was proposed by d'Arsonval in 1881, and Georges Claude demonstrated the open Rankine cycle process (Fig. 2) in 1930.[5] Warm water from the surface was drawn into a flash evaporator under vacuum, and the low-pressure steam produced drove a turbine and then was condensed by cold seawater, drawn from 700-m depth, which fell like rain in another evacuated chamber used as the condenser. Claude obtained the cold water by running a 1.6-m-diam by 1.75-km-long pipe into Mantanzas Bay, Cuba. From a seawater $\triangle T$ of 14°C, his turbine generated 22 kW$_e$. Because the turbine available to him was undersized by an order of magnitude compared to his cold-water pipe's flow capacity, this power output was less than his vacuum-pumping-power input; nevertheless he did demonstrate the principle.

In 1956 a French team, which had designed a 3.5-MW$_e$ (net) open cycle plant for installation

[2] F. C. Fuglister, *Atlantic Ocean Atlas of Temperature and Salinity Profiles and Data from the International Geophysical Year of 1957–1958,* Woods Hole Oceanographic Institute, Woods Hole, Mass., 1960.

[3] O. A. Roels, "The Economic Contribution of 'Artificial Upwelling' Mariculture to Sea-Thermal Power Generation," pp. 128–130 of Ref. 13.

[4] H. A. Wilcox, "The Ocean Food and Energy Farm Project," presented at *AIAA/AAS Solar Energy for Earth Conference,* Los Angeles, Apr. 21–24, 1975.

[5] G. Claude, "Power from Tropical Seas," *Mechanical Engineering* **52,** Dec. 1930, 1039–1044.

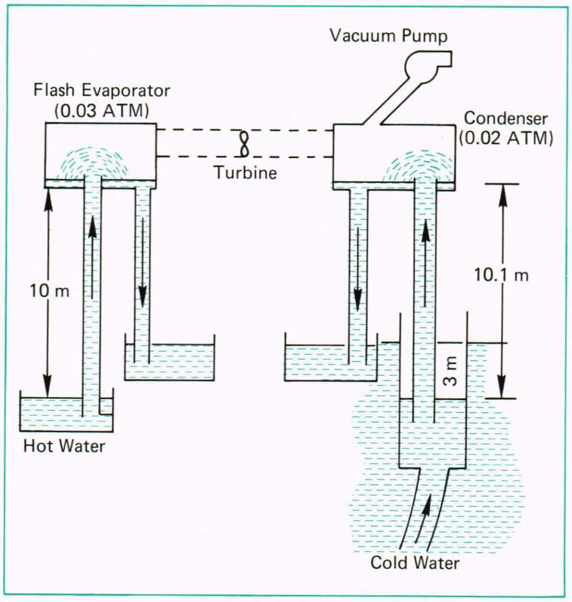

Fig. 2—Claude's basic open-cycle scheme for ocean thermal energy conversion (Ref. 5). Flash-evaporated seawater drives a turbine and is then recondensed by cold water falling like rain in the condenser.

off Abidjan on the Ivory Coast of Africa, demonstrated the necessary cold-water-pipe deployment. However, the project was judged to be marginal economically and was dropped when a hydroelectric plant was installed nearby.[6]

Improvements to Claude's open-cycle process have been described recently by Brown and Wechsler.[7] The primary concern has been the very large turbines required because of the very low steam pressure (0.03 atm), but Brown and Wechsler do not believe such turbines need to be expensive. They mention an analogy to helicopter rotors, as far as size goes, and suggest a lightweight blade construction similar to sailplane wings. Development work also would be needed on the direct-contact condensers.[7]

Still more recently Beck[8] and Zener and Fetkovich[9] have described possible improvements on the open cycle whereby systems analogous to air-lift pumps would raise the warm seawater to a substantial height from which it could fall to drive a water turbine of the type used in conventional hydroelectric plants. In Beck's original conception, the warm water would be introduced "through a restriction in the lower end of a vertical pipe. The resulting cavitation would provide the necessary nucleation for the formation of steam bubbles, which in a two-phase mixture [of greatly reduced density] would . . . [act as a] 'steam lift water pump,' . . . [At the top of an evacuated chamber] the steam-water mixture . . . would be separated, and the steam would be condensed in some variation of a barometric condenser [such as] used by Claude." Beck said that the maximum head could, in theory, be hundreds of feet, but a plant requiring a very tall tower above the sea could become unstable in tropical storms. Therefore, a more practical solution, which could make use of a head of a few tens of feet would operate as follows. "At the upper end of this lift pump the steam-water mixture would be deflected horizontally and the remaining available energy imparted to the water by the steam. The steam would be condensed just ahead of a nozzle delivering to a mixed flow water turbine. To achieve the large power desired in a single power plant, there would probably be many steam lift pumps delivering water to a single turbine runner."

Zener and Fetkovich's improvement[9] on Beck's concept would cause (presumably by use of some additive) the mixed liquid-vapor phase of the warm seawater to have a foam structure. In a plant having a chamber at the top evacuated to 0.126 psia (0.017 atm, corresponding to the vapor pressure of water at 5°C), the warm water would begin to foam at 25°C at a pressure of 0.458 psi. As the foam structure rose toward the lower pressure and continued to expand, with consequent gradual adiabatic cooling to 5°C, the water remaining as liquid would be carried in the corners of the foam cells. This foam lift process would be conducted in the annulus between two cylindrical pipes. When the foam reached the top of this annulus it would strike a foam-breaking barrier which would cause the liquid to drain back into the central pipe, to fall and drive a water turbine. The vapor would flow into an outer annular chamber (between the second pipe and a third pipe) where it would be condensed by contact with cold seawater at 5°C.

Zener and Fetkovich calculate a maximum theo-

[6] G. L. Massart, "The Tribulations of Trying to Harness Thermal Power," *MTS Journal* **8,** Oct.–Nov. 1974, 18–21.

[7] C. E. Brown and L. Wechsler, "Engineering an Open Cycle Power Plant for Extracting Solar Energy from the Sea," Paper OTC 2254, *Offshore Technology Conference,* Houston, May 5–8, 1975.

[8] E. J. Beck, "Ocean Thermal Gradient Hydraulic Power Plant," *Science* **189** July 25, 1975, 293–294.

[9] C. Zener and J. Fetkovich, "Foam Solar Sea Power Plant," *Science* **189,** July 25, 1975, 294–295.

retical foam lift height of 972 ft. However, that height "is obtained only when the available enthalpy is all converted into potential energy. But under these conditions the foam rises with a velocity approaching zero, and hence no power is developed. The maximum power per unit horizontal area is developed when the foam breaker is at two-thirds of its maximum height, 648 feet. For this height of the foam breaker, power is generated at the rate of 1.62 kw per square foot." Further compromise would be required, however, for the reason noted by Beck,[9] because a 100-MW_e heat engine would have, by this criterion, a 280-ft-diam tower rising some 700 ft above the sea, an unwieldly configuration that has not yet taken into account the needs for other platform and electric power delivery (or onboard use) features.

These potential improvements to open-cycle OTEC systems warrant further study but are judged by the writers and many other investigators to require more R&D than closed-cycle OTEC plants. As the Andersons pointed out in their landmark paper in 1966,[10] a closed-Rankine-cycle system employing a working fluid (e.g., ammonia, propane, or a Freon-type refrigerant) in an evaporator-turbine-condenser-pump loop (Fig. 3) could be developed quickly using existing technology drawn largely from the refrigeration/air-conditioning and desalination industries. In this approach the warm seawater provides the heat for the evaporator, and cold seawater cools the condenser. They estimated that a floating, 100-MW_e power plant, using submerged heat exchangers and propane as the working fluid, could be built at a capital cost of \$167/kW_e, comparable to construction costs at that time for fossil-fuel and nuclear power plants. Their estimate of power cost was 3 mills/kWh.

The APL interest in closed-cycle OTEC plants was triggered in January 1973 by an article by Zener.[11] The very encouraging preliminary results of our independent investigation of floating, tropical-ocean plants were presented in June 1973[12] at the first OTEC workshop, which was sponsored by NSF/RANN (National Science Foundation,

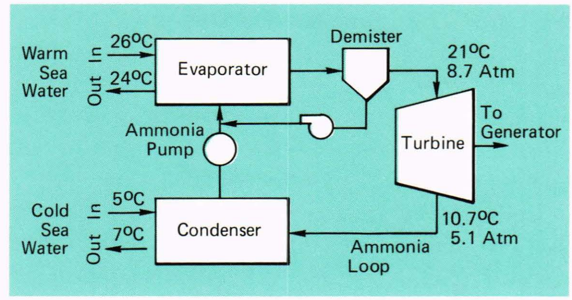

Fig. 3—Simplified loop diagram (for tropical ocean temperatures and ammonia working fluid) for the closed-Rankine cycle, Ocean Thermal Energy Conversion (OTEC) plant.

Research Applied to National Needs). At that time NSF was supporting a study of Gulf-Stream OTEC plants by the University of Massachusetts and had just made an award to Zener of Carnegie-Mellon University (CMU) for studies of heat exchangers and other system components by geometric programming techniques.

While seeking support for OTEC R&D from the Atomic Energy Commission (whose planned program in the solar energy area was not funded) and NSF, we continued a modest Laboratory-funded study which further convinced us of the great potential for the economic production of power and products at sea. In April 1974, NSF/RANN solicited both competitive OTEC system studies and original projects on the heat-engine components and other aspects of OTEC. As a Federal Contract Research Center, APL could not compete for the system studies, which were awarded to two industrial teams headed by TRW and Lockheed. We did propose an experiment to obtain performance data on two-phase-flow heat exchangers needed for our low-cost OTEC plant concept, but it was judged by NSF to be too ambitious and novel to be among the 20 projects (from 84 submissions)[13] that they chose to support with the available funding. However, we were subsequently funded by the new Energy Research and Development Administration (ERDA, which took over most of the energy R&D from NSF) to do a more detailed analysis of our heat exchanger concept and design a follow-on experiment, as well as to conduct the third OTEC Workshop in May 1975.[13] We also began a study in April 1975

[10] J. H. Anderson and J. H. Anderson, Jr., "Thermal Power from Sea Water," *Mechanical Engineering* **88,** Apr. 1966, 41–46.

[11] C. Zener, "Solar Sea Power," *Physics Today* **26,** Jan. 1973, 48.

[12] H. L. Olsen, et al., "Solar Sea Power Plant Conference and Workshop," A. Lavi, Editor, Carnegie-Mellon Univ., Pittsburgh, June 27–28, 1973, 185–204.

[13] G. L. Dugger, Editor, "Proceedings, Third Workshop on Ocean Thermal Energy Conversion," Houston, May 8–10, 1975, APL/JHU Report SR-75-2, Aug. 1975.

for the U.S. Maritime Administration (MARAD), Department of Commerce, to develop our plant concept further and to evaluate the maritime aspects of its construction, deployment, and operation, including the onboard production of ammonia and other potential products.

In the following section we shall briefly describe the four closed-cycle OTEC plant concepts developed by others under NSF/RANN support, the APL concept, the state of the art relative to various plant components, some of the environmental and socioeconomic considerations, some preliminary cost comparisons, and our estimate of the contribution that OTEC plants can make to U.S. energy needs if adequate support is provided for rapid development.

Recent Conceptual Designs for OTEC Plants by Others

Heronemus, McGowan, and coworkers at the University of Massachusetts have designed submerged catamaran configurations to be anchored in the Gulf Stream off the lower U.S. East Coast to deliver electric power to shore. Their "Mark II," 400-MW_e plant concept (Fig. 4)[14] is designed for the 18°C (32°F) ΔT available 25 to 50 km east of Miami, Florida. The turbines and the plate-and-fin-type condensers are housed in twin 24-m (80-ft)-I.D. × 183-m (600-ft)-long reinforced-concrete hulls. Banks of plate-fin evaporators are located (with pumps) in tiers of pods that are staggered in depth serially above the hulls to take advantage of the Gulf Stream current to reduce the pumping work. Use of 90/10 copper-nickel alloy, which is not compatible with ammonia in the condensers and evaporators, led them to choose propane for the working fluid. The aluminum cold-water pipe, supported by a gun-buckler-type joint between the hulls, reaches a depth near 400 m (1300 ft). It is elliptical in cross-section (29 × 24 m, or 95 × 80 ft) and rises at a 45° angle in the current's direction to reduce drag. The plant is tethered from the lower end of this pipe to an anchor. The power transmission cables, probably AC for distances less than

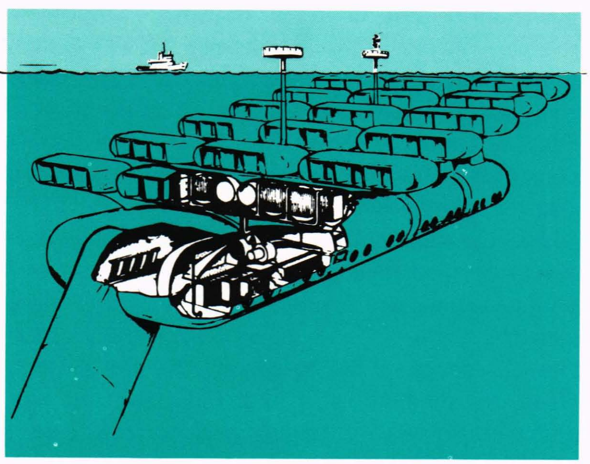

Fig. 4—The 400-MW_e, submerged-catamaran configuration "Mark II" OTEC plant design by the University of Massachusetts for use in the Gulf Stream off the lower U.S. East Coast (Ref. 14). The cold-water pipe at front supplies condensers in the twin hulls. The evaporators are in pods above the hulls.

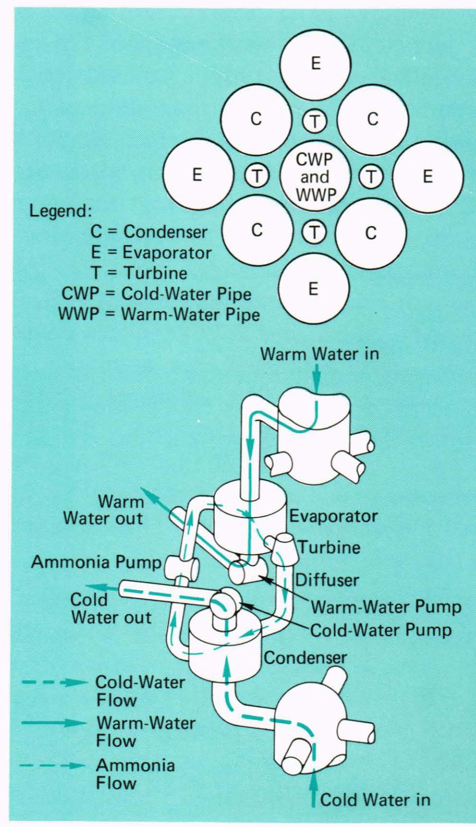

Fig. 5—Carnegie-Mellon University's modular scheme for a fully-submerged, unmanned plant. The warm-water pipe (WWP) inlet (with screen) is near the surface; the cold-water pipe (CWP) inlet (with screen) is at 500 to 700 m depth (Ref. 15).

[14] W. P. Goss, W. E. Heronemus, P. A. Mangarella, and J. G. McGowan, "Summary of University of Massachusetts Research on Gulf Stream Based Ocean Thermal Power Plants," pp. 51–62 in Ref. 13.

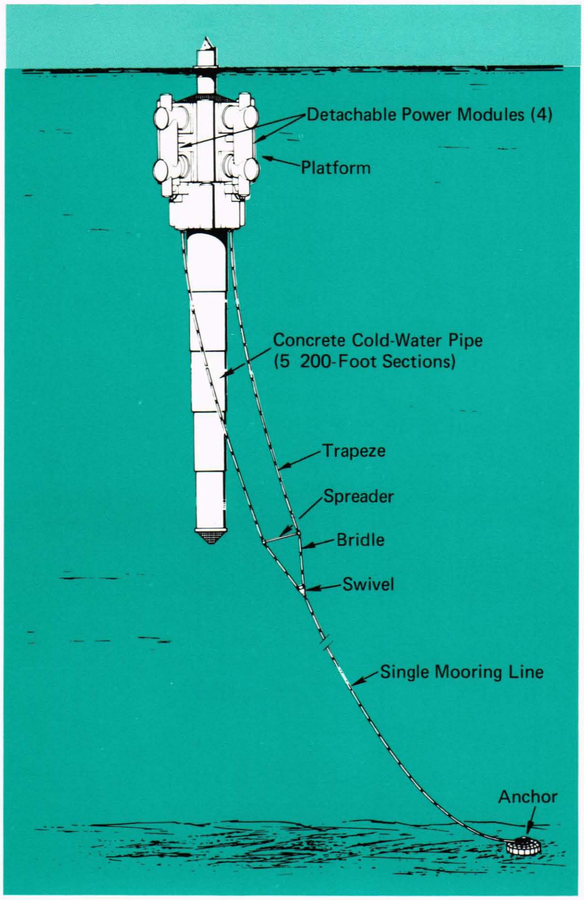

Fig. 6—The moored, spar-buoy type, 160 MW_e plant design concept of the Lockheed/Bechtel Corporation/ T. Y. Lin team (Ref. 16).

30 km to shore, or DC with converters on both ends for greater distances, run down the pipe to the ocean floor.

Zener and Lavi at Carnegie-Mellon University propose an unmanned, automated, submerged plant having multiple power modules (Fig. 5).[11, 15] They have devoted more attention to geometric programming to find optimum component designs. They advocate aluminum heat exchangers (to minimize cost) using fluted tubes which they expect to enhance the heat-transfer coefficients significantly,[15] based on earlier work on water-steam heat exchangers by the AEC's Oak Ridge National Laboratory.

The baseline plant design developed by Lockheed Ocean Systems, Bechtel Corporation, and T.Y. Lin International (hereinafter called "the Lockheed team") in their 9-month system study[16] is an anchored spar configuration (Fig. 6), primarily of reinforced-concrete construction. The telescoping, concrete cold-water pipe reaches 460-m (1500-ft) depth to provide 18°C (33.5°F) $\triangle T$. The main core vessel is 57-m (188-ft) I.D., and the maximum span across power modules is 126 m (412 ft). Total displacement is 300,000 tons. They provided many examples of large, reinforced-concrete structures that have demonstrated the necessary technology in that area. Four detachable power modules (Fig. 7) using titanium-tubed heat exchangers, with seawater inside and ammonia outside the tubes, generate a total net output of 160 MW_e. The plant is conservatively designed to permit use in the Gulf Stream (or other hurricane belts) as well as at tropical sites (with mooring depth limited to 6000 m) with a 100-yr system life expectancy.

The team of TRW Ocean and Energy Systems, Global Marine Development, and United Engi-

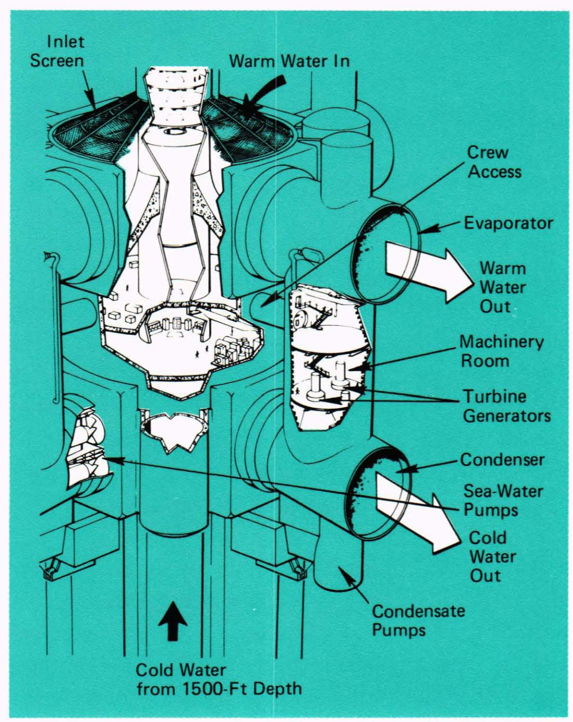

Fig. 7—Close view of one power module (of four) in Lockheed's plant concept (Ref. 16).

[15] A. Lavi, "Final Report, Solar Sea Power Project," Report NSF/RANN/SE/GI-39114/PR/74/6, Carnegie-Mellon University, Pittsburgh, Jan. 31, 1975.

[16] L. C. Trimble, B. L. Messinger, H. G. Ulbrich, G. Smith, and T. Y. Lin, "Ocean Thermal Energy Conversion System Study Report," pp. 3–20 in Ref. 13.

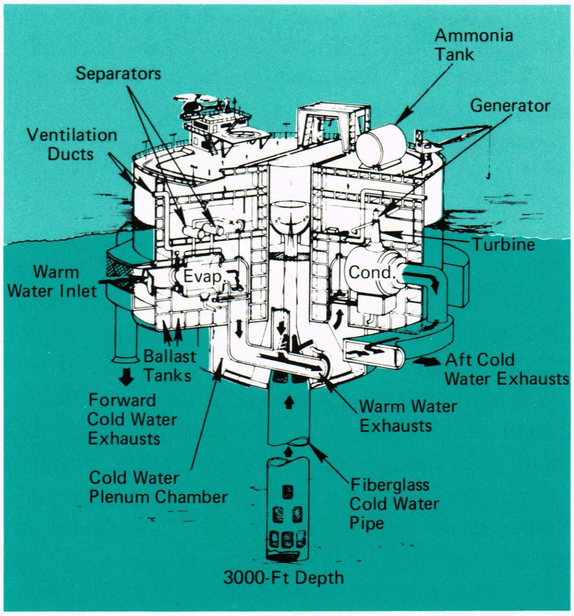

Fig. 8—The floating, cylindrical-surface-vessel, 100-MWe plant design concept of the TRW/Global Marine/United Engineers and Constructors team (Ref. 17). Shrouded-pipe water jets (condenser discharge and part of the evaporator discharge) control the plant position.

neers and Constructors (hereinafter called "the TRW team") briefly investigated 3 spar-buoy, 6 semisubmersible, and 6 surface-vessel configurations before selecting the cylindrical one shown in Fig. 8 for their baseline design.[17] It is 103 m (340 ft) in diameter, displacing 213,000 tons, and is designed for a 40-yr life. Four power modules inside the reinforced-concrete hull yield a total net output of 100 MW_e. As in the Lockheed team's baseline design, the heat exchangers use titanium tubes with ammonia outside the tubes. The cold-water pipe is made of fiber-reinforced plastic and reaches a depth of 1220 m (4000 ft) to achieve a 22°C (40°F) $\triangle T$ in tropical oceans. They judge that a dynamic positioning system (using the warm-water discharge and part of the cold-water discharge in shrouded jets) will be less expensive and more reliable than a mooring system for use in tropical oceans.

One question often asked about closed-cycle OTEC plants is, why not put the condensers at depth and eliminate the large cold-water pipe? The reasons are that (a) the power required to pump the working fluid as vapor to that depth and to pump it back up as liquid exceeds that of pumping the seawater up, and (b) the condensers would have to be much heavier and costlier to withstand the hydrostatic pressure at depth.

The foregoing studies have been limited primarily to the basic power plant. The APL work for MARAD is at the forefront with respect to use of the power for onboard production of ammonia or other products, as will be required to make greatest use of the tremendous tropical ocean resource. The Institute of Gas Technology has also begun a study of the production of hydrogen and ammonia at sea,[13] and DSS Engineers, Inc. has begun a study of ocean industrial complexes.[13] (The Andersons, in various papers, presented preliminary estimates for production of fresh water together with power, and suggested production of hydrogen and methanol, as well as mariculture.)

The APL OTEC/Ammonia Plant Concept

The tropical-ocean OTEC plant-ship concept, which is presently undergoing more detailed analysis under the aforementioned study for MARAD, can be described in general terms.[18] The general arrangement is of the surface-vessel type, but there are some similarities to oil-drilling and ocean-mining platforms, as illustrated in Fig. 9. The platform has a beam of 60 m (196 ft, to stay within existing capabilities of several U.S. shipyards), a length of about 145 m (475 ft) and a displacement of about 55,000 metric tons including the onboard ammonia plant and 10,000 tons of product storage. This displacement is based on steel construction, but some use of concrete may prove more economical while raising the displacement figure.

Large banks of submerged evaporator and condenser modules are located below the deck openings. The central cold-water pipe is approximately 18 m (60 ft) in diameter and extends to 750 to 900 m (2500 to 3000 ft) depth. Aluminum and steel designs are being considered for this pipe; the fiber-reinforced plastic approach selected by TRW also looks attractive. The exit flows from

[17] R. H. Douglass, "Ocean Thermal Energy Conversion: An Engineering Evaluation," pp. 22–36 in Ref. 13.

[18] G. L. Dugger, H. L. Olsen, W. B. Shippen, E. J. Francis, and W. H. Avery, "Floating Ocean Thermal Power Plants and Potential Products," to be published in *Journal of Hydronautics*, October 1975 (a revision of AIAA Paper 75-617, April 1975).

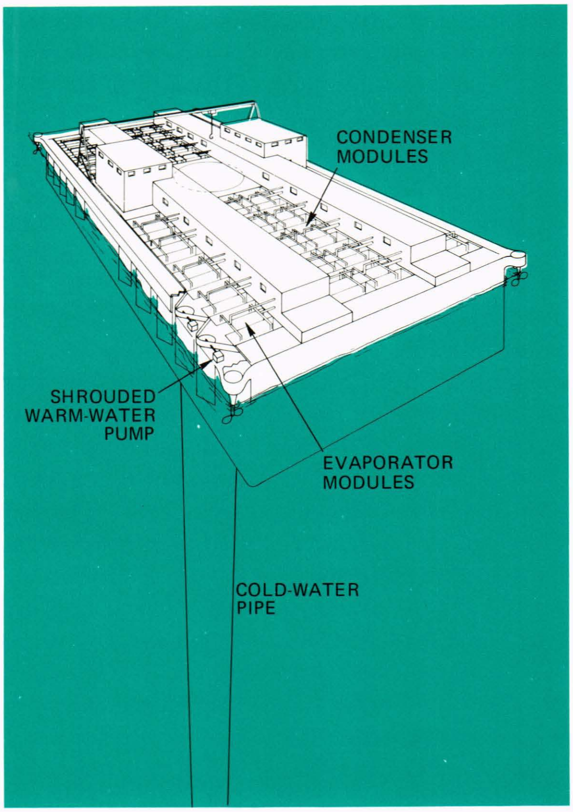

Fig. 9—The APL/JHU concept for an OTEC plant-ship for producing ammonia. The cold-water pipe brings water to the central well to flood banks of multi-module condensers below the deck openings nearest it. Outboard warm-water pumps flood banks of multi-module evaporators.

the evaporators and condensers could be directed to assist in station-keeping or in "grazing" movements in the mild 0.5-knot currents in which the plant is intended to operate.

Simple, two-phase-flow heat exchangers with large diameter (15 to 22 cm, or 6 to 9 in.) aluminum tubes are used to minimize first cost and maximize the possibility of a quick payoff for early OTEC plants. The ammonia working fluid flows inside the multipass tubes, which are folded 14 or more times. The seawater flows downward in a single pass from a head tank at the top. Both vertical (parallel to seawater flow) and horizontal (cross-flow) orientations of the multipass tubes are being analyzed. We see the following advantages for this approach.

1. Although the required heat-transfer-surface area is increased somewhat with the large-diameter tubes, the cost of fabrication should be lower. Overall heat exchanger cost is expected to fall in the range \$1.50 to \$3.00/ft^2 of heat transfer surface,* based on an estimated cost of 80¢/lb for fabricated aluminum tubing,[19] compared to \$9/ft^2 or more for shell- and titanium-tubed heat exchangers.[16,17]

2. The "shells" of the heat exchangers will have seawater on both sides with very little pressure differential, so that they can have thin walls and rectangular cross-sections to facilitate multi-modular arrangements. The resulting flexibility in module design facilitates the design of an economical overall plant-ship configuration along the lines suggested by Fig. 9 to take advantage of the relatively benign, tropical-ocean environment. A low-draft (prior to cold-water pipe installation) plant-ship design, rather similar to oil drilling platform designs, also will facilitate construction in existing U.S. shipyards and deployment to distant ocean sites.

3. The use of approximately 100 heat exchanger modules (driving approximately 16 ammonia turbines) to make up a 100-MW_e net output plant will permit cleaning, repair, or replacement operations, one module at a time, without appreciable reduction in power output. A water-jet cleaning system being developed by Hydronautics, Inc., shows promise of being usable *in situ* and may not even require module shutdown during the cleaning operation, since the seawater path through the modules will be open and accessible at all times to a translatable, multiple-head, water spray device.

The warm seawater is pumped into head ponds above the banks of evaporator modules by a series of pumps mounted vertically along the outboard sides of the platform. The cold seawater is raised through the 60-ft-diam central pipe by a number of pumps installed within the top of the pipe and flows to head ponds over the banks of condensers. The seawater flows by gravity in a single vertical pass through the heat exchangers. The discharged warm water (cooled approximately 2°C below its original temperature by the heat exchange) will sink toward the bottom of the ocean's mixed surface layer (above the thermocline at 50 to 100 m depth). The cold water (discharged at approxi-

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* The cost assigned in \$/ft^2 of heat-transfer surface will depend upon the tube diameter and design details finally chosen, including the degree to which the "shells" serve as structural elements of the plant-ship.

[19] Private communication from T. R. Pritchett and associates, Aluminum Div., Kaiser Aluminum and Chemical Corporation, Center for Technology, Pleasanton, Calif., to W. H. Avery, APL/JHU, Apr. 18, 1975.

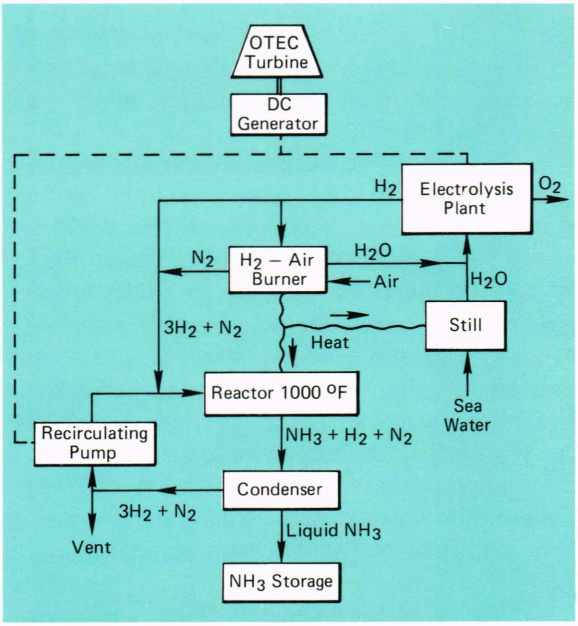

Fig. 10—Block diagram for an OTEC-NH_3 plant.

mately 7°C) will sink to the depth (500 to 700 m) at which its density matches the ambient value. Since the plant will always be moving at a small velocity (say, ½ knot) relative to the water, it will move away from these effluents, so there will be no danger of reingesting water that has already been cooled (or heated) by it.

It should be noted that the displacement for the basic ship and power plant (with aluminum heat exchangers) will be much smaller than the displacements for the baseline plant concepts of TRW and Lockheed (adjusted to 100-MW_e size), which employ large enclosed volumes. Thus the platform cost will be lower. (TRW[17] has also stated that platform cost could be reduced by locating the heat exchangers outside the hull.)

The concept for onboard ammonia production is illustrated in Figs. 10 and 11. The electric power produced is used to make hydrogen by electrolysis of water that is distilled onboard. The nitrogen for the ammonia synthesizer is obtained by burning oxygen from air with approximately 1/7 of the gaseous hydrogen from electrolysis cells to form water, leaving nitrogen plus the minor constituents of air, mainly argon and CO_2. (The presence of the latter gases will require fractional venting with a resultant slight loss of product ammonia.) The water vapor is condensed and returned to the electrolysis cells. The heat produced by the burner is used in part to operate the seawater still to produce the rest of the water needed for the electrolysis cells (which also provide some heat for the still) and in part to provide heat to the catalytic converter. The remaining gas from the burner is mixed with the remaining 6/7 of the hydrogen from the electrolysis cells in a molar ratio of 1 N_2 to 3 H_2 and fed to the ammonia synthesizer, which uses a promoted-iron or other catalyst. A condenser then removes a portion of the ammonia as liquid, and the remaining gases are recirculated through the synthesizer by a compressor.

This ammonia plant would use the same type of catalytic-ammonia-synthesis and liquefaction equipment as do existing commercial plants but without the most costly and maintenance-demanding gas- or oil-reforming portions of those plants. Further use of the oxygen produced by the elec-

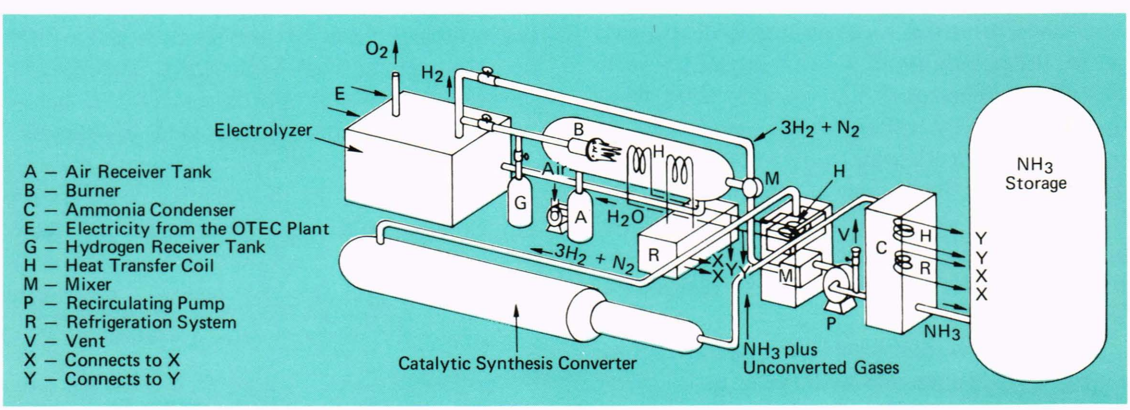

Fig. 11—Schematic arrangement of an NH_3 plant for the OTEC platform.

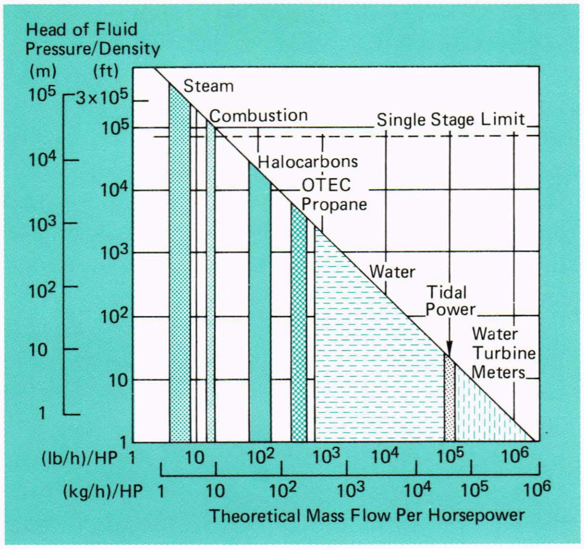

Fig. 12—The spectrum of turbines.

trolysis cells is not credited here, but it might eventually prove economically attractive to liquefy the oxygen for shipment to shore for use in waste-treatment plants.

Technology Status for the OTEC Plant Components

Turbine Technology—Turbine design will be relatively straightforward. Figure 12 (after a figure by J. Hilbert Anderson) shows where all known turbines fit in terms of head (m or ft) vs theoretical mass flow per horsepower obtained. The turbines for OTEC plants will fall between the hydroelectric water turbines and combustion gas turbines. Since the plant is expected to operate at essentially constant load (no significant variation in turbine rpm required), a specific design point for high efficiency can be selected. Turbine materials can be rather pedestrian because the tip speeds, pressures, temperatures, and temperature variations will be very moderate compared with those for conventional steam or gas turbines. Several U.S. manufacturers stand ready to build such turbines.

Figure 13 shows estimates[20] of turbine characteristics for a Gulf Stream plant (32°F ocean ΔT) based on a turbine specific speed of 100 and specific diameter of 1.3, near optimum values. As design power output increases, diameter D increases and rotational speed N decreases. Propane turbines are larger and slower than ammonia turbines, and cost nearly twice as much. The available ocean ΔT also will have a strong effect on turbine cost, since plant efficiency varies with the ΔT raised to a power between 2 and 3. Thus, an increase in ΔT from 17.8°C (32°F) to 23.9°C (43°F) by going to a tropical ocean site could reduce the turbine cost by approximately 50%. From cost estimates in Ref. 20 we estimated that the installed costs of turbine/generator sets for a tropical OTEC plant would be in the range \$50 to \$60/$\mathrm{kW_e}$ net in 1973 dollars.

The Heat Exchangers—The heat exchangers will be the largest and most costly components on the basic OTEC plant, because the available temperature differences are small, more similar to those in refrigeration/air-conditioning equipment than in the boilers and condensers in conventional power plants.

The thermodynamic properties of the working fluid selected will have a great influence on heat-exchanger and turbine sizes and hence system cost. Ammonia is by far the most attractive thermodynamically.[12] It has some disadvantages (it is toxic, mildly corrosive when wet, and does not dissolve oil). However, precautions developed in the fertilizer and refrigeration industries should suffice for its safe use, and environmentalists say that leaks of it would have less impact than a propane or Freon leak.[17] Propane is next best thermodynamically, it is noncorrosive, and has a

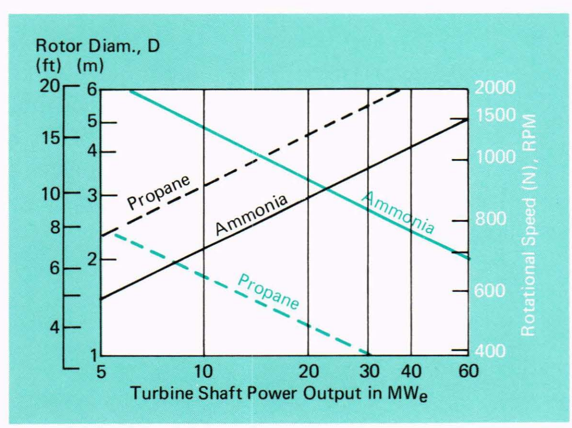

Fig. 13—Turbine characteristics for propane and ammonia working fluids for an OTEC plant in the Gulf Stream (Ref. 20).

[20] R. D. Lessard, "Technical and Economic Evaluation of Ocean Thermal Difference Powerplant Turbomachinery, Energy Program," Report NSF/RANN/SE/GI-34979/TR/73/18, University of Massachusetts, Amherst, Dec. 1973.

similar working pressure range—80 to 150 psia—but its mass flow rate would have to be more than three times as great. One of the Freons (halogenated hydrocarbons) would offer the advantage of nonflammability but would be still lower in performance.

In the evaporators there may be a problem of biofouling from organisms that flourish in the warm water. This problem can be minimized by keeping the water velocity above 1.5m/sec (5 ft/sec) and, in general, by locating the plant far from shore, but it may be necessary to provide a means for either regularly cleaning the surfaces on the seawater side (e.g., by the water-jet system mentioned earlier) or preventing the biofouling (e.g., by adding 0.1 to 0.3 part per million of chlorine to the seawater either batch-wise or continuously). Biofouling will be a smaller, perhaps negligible, problem in the condensers, because there will be far fewer organisms in the cold water drawn from great depths.[21]

Material selection will represent a compromise. Most structures for use in seawater are made of steel, which is protected from corrosion with a special paint or coating or may be given good corrosion resistance with cathodic protection.[22] For the heat-transfer surfaces, the 90/10 copper-nickel alloy commonly used in marine condensers (and considered by the University of Massachusetts team) has excellent thermal conductivity, it is resistant to fouling, and could be used with propane as the working fluid, but it is expensive, it is not compatible with ammonia, and the copper leached from it would have an adverse environmental impact. Titanium (selected for the baseline concepts of the TRW and Lockheed teams) has excellent corrosion resistance except for galvanic corrosion, but is very costly. Aluminum, in suitable alloys which are practically inert to seawater[23] and are much lower in cost than Cu-Ni or Ti, has proven very satisfactory for heat exchangers for desalting plant use.[24] It also has very good thermal conductivity. Thus, an aluminum alloy would appear to be more cost effective for the heat exchangers.

The APL concept of using two-phase flow of ammonia in multipass tubes requires experimental verification of the computed performance, because the available, pertinent experimental data are quite limited,[25] and none deal with the overall system arrangements under study. However, it is believed that this verification can be obtained by tests in approximately one year's time.

The Cold-Water Pipe (CWP) and Seawater Pumps—Fabrication and deployment of the cold-water pipe for an OTEC plant will be a challenging engineering/logistics problem, just as it was for Claude in 1930[5] and the French team in 1956.[6] However, the facts that (a) they did deploy pipes successfully, (b) oil, gas, and water pipelines are criss-crossing North America, and (c) complex oil-drilling, mining, and other offshore rigs are becoming commonplace, provide assurance that there will be practical solutions to this problem.

For 100 MW_e net power output, a CWP of 15 to 18 m (50 to 60 ft) diameter will be needed to pump approximately 1.8 billion kg/hr (7.5 million gpm) of seawater through the condensers. These flow figures are based on an overall ΔT near 24°C with ammonia as the working fluid, and parasitic pumping power losses near 20% (125 MW_e gross output to net 100 MW_e). The design of the CWP will be determined by the plant location (the ΔT vs depth tradeoff) and the overall system efficiency/cost-effectiveness tradeoff, which involves many parameters. For a 900-m (3000-ft)-long CWP for a 100-MW_e plant, pumping power for the CWP (comprising the loss due to friction in it, the head loss due to seawater density change with depth, and the dump loss from it to the condensers) will be approximately 6 MW_e for an 18-m diameter (approximately 2 m/s or 6 ft/s water velocity), or less for a larger diameter. The pumping power required for the evaporator(s) and condenser(s) will be approximately 5 MW_e each. The ammonia pumping power requirement is relatively small unless there is a need to recycle vapor from the condensers. Auxiliary machinery and ship/crew needs will add 3 to 6 MW_e.

[21] E. C. Haderlie, Naval Postgraduate School, Monterey, Calif., private communication with W. B. Shippen and E. J. Francis, APL/JHU, Mar. 4, 1975.

[22] L. D. Webb, "Uses of Metals in Offshore Structures," *Oceanology International,* **5,** Mar. 1970, 19–23.

[23] F. W. Fink and W. K. Boyd, "The Corrosion of Metals in Marine Environments," DMIC Report 245, May 1970, Defense Metals Information Center Battelle Memorial Institute, Columbus, Ohio.

[24] E. D. Verink, Jr., "Aluminum Alloys for Saline Waters," *Chemical Engineering* **81,** April 15, 1974, 105–110.

[25] L. Pujol and A. H. Stenning, "Effect of Flow Direction on the Boiling Heat Transfer Coefficient in Vertical Tubes," *Concurrent Gas-Liquid Flow,* Edward Rhodes and Donald S. Scott, Editors, Plenum Press, N. Y., 1969, 401–453.

Among the CWP materials under investigation are aluminum, steel, fiber-reinforced plastic,[17] and reinforced concrete.[16] The telescoping concrete design[16] has not been evaluated for use for depths greater than 1700 ft.

The seawater pumps will be comparable in size to the largest water turbines in hydroelectric plants. Such pumps are available but are rather costly; some development to reduce production cost would be appropriate.

Environmental and Social Impacts

As for all other solar energy conversion systems, the basic ocean thermal energy conversion (OTEC) plant would be very attractive ecologically compared to fossil-fuel or nuclear power plants, because it would be "fueled" by a portion of the inexhaustible supply of energy from the sun and would be nonpolluting. In contrast to all the other solar and nonsolar types, however, it would use no precious land area or visible structures for power generation or energy storage to accommodate noninsolation periods—the only land use requirements would be for power transmission substations tying into a utility grid and/or the storage that will be needed anyway for products that might otherwise have to be imported from foreign land-based plants.

With respect to ecological impact in the oceans, further studies are needed, but a few points can be made. If no changes in ocean surface layer absorptivity, currents, or mixing were induced by the power plant operation, the 2% or so local utilization of incident solar energy could (at worst) be compensated by the same percentage reduction in surface cooling by water evaporated from the ocean surface. Thus, if it is assumed that evaporation rate is proportional to water vapor pressure, the surface temperature within the area of influence of the plant would eventually be lowered from 26.5°C to 26.1°C. But the effect will not be even this large, because the peak insolation far exceeds the average value, and a cooler layer would absorb more of this energy, which would be distributed by mixing and currents. Bathen[26] used local weather data (including wet-bulb temperatures) and surface water temperatures to calculate heat balances for the air-sea interface off Keahole Point, Hawaii, for average winter and summer conditions with and without the presence of an 0.8°C anomaly due to a cold-water discharge and concluded that the net heat budgets at the interface would increase, both winter and summer. He also did a hydrodynamic analysis for cold-water-discharge plume mixing for a 20-MW_e OTEC plant off Keahole Point and concluded that the impacts could be equivalent to temperature drops in the mixed layer (above the thermocline) of just 0.02°C/0.07°C during winter/summer conditions, over areas of only 1.1 km^2/2.6 km^2, respectively. Such small temperature changes are well below the typical diurnal changes of 0.1°C/0.3°C, respectively.

The cold water brought from the deep to cool the condenser is rich in nutrients that significantly enhance fish growth and could provide an ecological plus, whether or not a deliberate attempt is made to pursue mariculture near OTEC plants. The landings of fishery products by the U.S. have lagged far behind those of other nations and have been only one-third those of Japan, USSR, or Peru.[27] Upwelling of cold water has led to large catches of sardines off Peru, and previously off California. The possibility of reaping benefits near, or downstream of, OTEC plants should be included in environmental impact investigations. Bathen's analysis, again for the effects of a 20-MW_e OTEC plant off Keahole Point, Hawaii, indicated that nutrient levels in surface waters would increase by 300% at a 260-m radius from the cold water discharge point, resulting in a 1500% increase in phytoplankton and a 540% increase in herbivores. Thus, the required strategy for a combined OTEC-mariculture operation would be to assure operation in a small current and direct the discharges downstream to the mariculture farm to avoid added biofouling problems and efficiency ($\triangle T$) effects on the plant.

Although normal operation of an OTEC plant would produce no chemical pollution of air or water, impact studies will be needed to assess the potential consequences of a spill of the working fluid, which might be ammonia or propane. With appropriate instrumentation and monitoring of plant performance, it should be possible to detect spills early and take action before they reach a

[26] K. H. Bathen, "Oceanographic and Socio-Economic Aspects of an OTEC Proof-of-Concept Test Site in Hawaii," pp. 162–171 in Ref. 13.

[27] C. E. Jahnig, Triton Seafarms Co., Rumson, N. J. (an Exxon and APL/JHU Consultant), private communication to W. H. Avery, APL/JHU, Feb. 1974.

significant magnitude. It would be expected that all major components of an OTEC plant would be designed for at least a 20-year life and would be inspected at reasonable intervals just as the components of stationary power systems are.

Another factor needing study is possible interference with shipping lanes, but operation of unmoored, grazing plants in tropical seas beyond territorial limits would be equivalent to other commercial shipping on the high seas to which the present Law of the Seas applies. Legal considerations are being studied for ERDA.[13]

Relative to the OTEC plant's ability to draw warm water from the mixed layer without drawing cold water from below the thermocline into the evaporators, Zener[28] has estimated that for a surface current of 0.03 m/sec (0.2 knot), OTEC plants up to 400-MW_e size could operate without a problem. The presence of a larger current (or relative speed of a grazing plant) would permit an increase in plant size based on this criterion, but it seems unlikely that early plants will exceed 500 MW_e anyway, because economies of scale probably will not be significant above that size.

Cost Estimates for Producing Power and Products

Only approximate cost estimates for OTEC plants can be made until performance data for a pilot plant embodying the basic features of a complete system are available, a demonstration plant has been run, and economies of scale, as well as of large production runs of the power module components, have been fully evaluated. Nevertheless, cost estimates are of interest to indicate the relative competitive position seen for OTEC plants in the near future.

A simple comparison with recent cost estimates for fossil-fuel and nuclear power plants[29] is presented in Table 1. An OTEC plant with an uninterruptible energy source and modular design, permitting an average use factor of 0.9, could have a capital cost, including means for getting the energy to shore, of \$1000/kW_e and be competitive with a nuclear fission plant at approximately \$500/kW_e and superior to a coal plant at approximately \$450/kW_e using eastern coal at \$28.50 to \$37.00/ton. The OTEC cost could go to \$2500/kW_e if 10% fixed-charge rate could be attained and if it were competing with a nuclear plant at \$1000/kW_e or an oil-fired plant using oil at \$11/bbl. The fixed charges for this comparison are taken to be 15% for the land-based plants, and 13% or 10% for tropical OTEC plants, which will be subject to no local taxes, although they may have somewhat higher insurance costs. The 10% rate is based on Export-Import Bank financing at 6% interest rate and reduced insurance cost.[30]

Table 1

APPROXIMATE POWER COST COMPARISONS FOR NEW CONSTRUCTION TO ESTIMATE ALLOWABLE COMPETITIVE COST FOR AN OTEC PLANT (WHICH MUST INCLUDE THE COST OF GETTING THE POWER TO SHORE)

	Fossil Fuel *Oil*	*Coal*	*Nuclear* *Low-High*	*Allowable OTEC range*
Investment, \$/kW_e	465*	450*	500*–1000	1000–2500
Use factor*	0.75	0.75	0.6	0.9
Fixed charge rate	15%	15%	15%	13–10%
Costs, mills/kWh:				
Fixed charge	11	10	14–29	17–32
Operating cost	1	1	1	1
Fuel cost	20†	11–14†	3	0
Power cost	32	22–25	18–33	18–33

* Values from Ref. 29. Costs include \$100/kW_e for pollution and safety control costs, and costs for fossil fuel plants include 30-day fuel storage facilities.

† Oil at \$11/bbl and eastern coal at \$28.50 to \$37/ton. Based on heat rate of 10,000 Btu/kWh.

Table 2 compares capital cost estimates for OTEC plants from three sources: the University of Massachusetts group,[14] ours (APL/JHU),[18] and the Carnegie-Mellon University (CMU) group, who presented "low, medium, and high" estimates (medium shown here).[15] For comparison, the estimate from the University of Massachusetts for propane working fluid has been converted to use of ammonia in the second column. These various estimates are remarkably consistent when the strong effects of the seawater ΔT and the working fluid are taken into account.

The cost estimates of the Lockheed team[16] and the TRW team[17] for their baseline designs are

[28] C. Zener, "Site Limitations on Solar Sea Powerplants," AIAA Paper 75-618, *AIAA/AAS Solar Energy for Earth Conference*, Los Angeles, Apr. 21–24, 1975.

[29] "Solar Energy Task Force Final Report, Project Independence Blueprint," Federal Energy Admin., Washington, D. C., Oct. 4, 1974.

[30] "Export Import Bank Program Review," Senate Report S241-6, Feb. 1974.

Table 2

ESTIMATES OF CAPITAL COST, \$/kW$_e$ (1974 DOLLARS), FOR OTEC POWER PLANTS, EXCLUDING POWER (OR PRODUCT) TRANSMISSION TO SHORE

Source	*U. Mass.*[14]		*APL/JHU*[18]		*CMU*[15]
Plant site	Gulf Stream		±10° Latitude		—
Ocean ΔT, °C (°F)	18(32)		22(39)	24(43)	20(36)
Working fluid	Propane	NH_3*	NH_3	NH_3	NH_3
Costs, \$/kW$_e$ net:					
Heat exchangers	340	254	153	120	280
Turbines, generators, pumps, misc.	179	100	109	90	282
Cold water pipe	63	63	45	40	58
Platform	48	48	50	43	36
Total, \$/kW$_e$	630	465	357	293	656

* The U. Mass. estimates for use of propane working fluid from Ref. 14 were adjusted for use of ammonia by G. L. Dugger.

based on early 1975 dollars and are considerably higher than those in Table 2, which were based on 1973–74 inputs. They chose titanium-tubed heat exchangers with seawater inside the tubes for "immediately buildable," long-life baseline designs because of the corrosion resistance of titanium and the fact that its relatively hard surface (compared to aluminum) would permit use of conventional mechanical/abrasive methods to clean them. This conservative approach was consistent with the guidelines given them for their baseline studies. The resulting baseline estimates are \$2100/kW$_e$ by TRW (for a 40°F $\triangle T$) and \$2600/kW$_e$ by Lockheed (for a 34°F $\triangle T$). Approximately 50% and 58% of these costs, respectively, are for the heat exchangers, whose costs, both teams note, could be reduced by 40 to 70% by improved designs based on aluminum. Both teams also recognize the strong desirability of getting capital costs down for "nth production plant" designs. The Lockheed team stated that with only minor technical improvements, including aluminum coil-panel heat exchangers, costs could be reduced substantially. They also detailed a series of possible heat-exchanger improvements and other factors (including higher ocean $\triangle T$) that could ultimately lead to a heat exchanger cost as low as \$200/kW$_e$ with sheet-metal construction.[16] The TRW team notes that major cost reductions might be achieved in the platform as well as the heat exchangers and can foresee getting the plant cost down to \$1100/kW$_e$.[17]

Thus, an overall conclusion can be drawn that the estimates of cost from these studies by industrial teams, which have added greatly to the credibility of near-term development and demonstration of OTEC plants, are not nearly as far from those in Table 2 as would appear at first glance. At this writing, the organizations represented in Table 2 still believe that costs not far different from those in Table 2 (except for inflation) should be achievable for plants which are designed to minimize both heat-exchanger and platform costs. For example, the Carnegie-Mellon group believes that heat exchangers achieving high heat-transfer coefficients at low cost with fluted aluminum tubes will be practical and that plants may be fully submerged and fully automated, therefore essentially unmanned. The writers believe that plants specifically designed for use in the doldrum regions of the tropics and for direct integration of an ammonia (or other) plant on board (as discussed

Table 3

ESTIMATED POWER COSTS AT SHORE FOR GULF STREAM PLANTS (BASED ON CAPITAL COSTS FROM REF. 14 AND 32°F ΔT)

	Working Fluid					
	Propane			*Ammonia*		
Capital costs, \$/kW$_e$:						
Basic OTEC plant	630			465		
Power conversion/transmission system to shore	83			83		
Subtotal	713			548		
Add 12% for interest and escalation during construction	85			66		
Total capital cost, \$/kW$_e$	798			614		
Fixed charge rate, %	15	13	7	15	13	7
Costs in mills/kW$_e$h:						
Fixed charge at 0.9 load factor	15	13	7	12	10	5.4
Operating cost	1	1	1	1	1	1
Power at shore	16	14	8	13	11	6.4

hereinafter) will have the lowest effective power-plant capital costs and busbar power costs. With these comments in mind, the following Tables 3 to 5 (based on estimates from Table 2) are presented with the caution that some cost escalations are to be expected, but the relative cost changes should not be great enough to alter substantially the foreseen attractive competitive capability of OTEC plants. Insofar as inflation is concerned, it probably will affect the other systems in Table 1 (via fuel costs) more than it will affect OTEC plants.

Table 3 shows the University of Massachusetts estimates for total capital cost of getting the power to shore, including effects of interest and escalation during construction. These capital costs are well below the "allowable" range in Table 1. We have converted them to power costs for three assumed fixed-charge rates, 15%, 13%, and 7%, the last being typical of public utility financing a few years ago.

Production of ammonia at a tropical OTEC plant is attractive socially and economically for the following reasons.

1. Ammonia is a major item of national and international commerce used in the manufacture of many chemicals and other products. Its principal use is in the production of fertilizers critically related to world food production. Its price has been escalating rapidly.

2. Ammonia plants in the U.S. now consume 2½% of our natural gas supply. The forecast U.S. production of natural gas indicates a 35% decrease by 1985, while annual demand for natural gas is expected to increase by 5 to 6% per year. The result is a projected shortfall of 40 trillion cubic feet. The domestic ammonia picture is correspondingly bleak. If existing plants continue to receive as much gas as they do today, the projected ammonia shortfall by 1985 is 10 million tons (Fig. 14).[31] Use of U.S.-owned OTEC plants to provide this 10^7 tons/yr would help our balance of payments while saving the equivalent of 220,000 barrels of oil per day. The demand for fertilizers will continue to increase beyond 1985, and foreign needs for ammonia could generate export sales of OTEC ammonia plants.

3. Production of ammonia at the OTEC plant would require only hydrogen from seawater and nitrogen from air.

The estimates shown in Table 4 suggest that liquid ammonia could be delivered to U.S. ports from distances of about 4000 miles at a *cost* (before profit and income taxes) of $63 to $72/ton (1974 dollars), compared to recent *price* quotations of $145 to $165/ton at the plant gate or $215 to $245/ton delivered. Thus, there appears

[31] "International Trade in Ammonia May Rise Sharply," *Chemical & Engineering News* **52,** Aug. 5, 1974, 13–14.

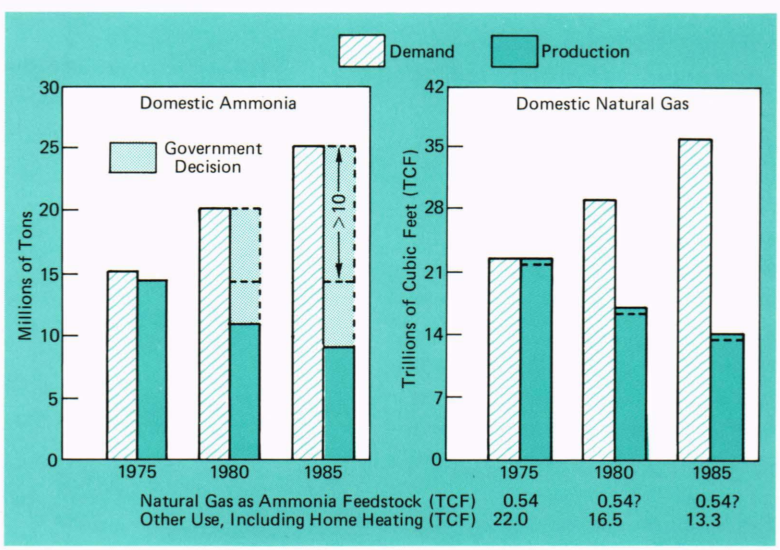

Fig. 14—Forecasts of U.S. demand and production for ammonia, assuming it continues to be made from natural gas, whose supply diminishes by 35% by 1985.

Table 4

ESTIMATED COSTS FOR PRODUCING AMMONIA AT A TROPICAL OTEC PLANT WITH 39°F ΔT

Plant cost to busbars (Table 2), $/kW$_e$		357
Add ammonia plant (Fig. 14)		90
Total plant investment, $/kW$_e$		447
Basis: 500 MW$_e$ plant producing 475,000 ton/yr		
Plant investment (P.I.), $/ton-yr		470
Working capital, $/ton-yr		20
Total capital required, $/ton-yr		490
Costs in $/ton for two methods of financing*†	Conventional	ExIm Bank†
Catalyst, chemicals, labor and overhead, $/ton	2	2
Maintenance (1% of P.I.)	5	5
Insurance (2%, 1% of P.I.)	9	5
Depreciation (20 yr, 5% of P.I.)	24	24
Interest (8%, 6% of ½ P.I.)	19	14
Production cost, subtotal	59	50
Interest on working capital	1	1
Shipment to U.S. port	12	12
Cost at port, $/ton	72	63

* Based on type of ammonia production costing used in Ref. 32. Maintenance is lower than in Ref. 32, because only a portion, which requires least maintenance, of a natural-gas-fed ammonia plant is needed here.
† The Export-Import Bank (ExIm) is currently funding about $10 billion/yr similar industrial projects at 6%, with longer repayment period loans frequently combined with private financing; in 1970, an ammonia plant was funded (Ref. 30).

to be considerable margin available for achieving a competitive production cost. In the future, the fossil fuel used as feed to U.S. landbased ammonia plants may have to be changed from natural gas to coal, which would substantially increase the competing landbased production cost. The interfacing problems for liquid ammonia would simply relate to expansion of shipping and port handling capabilities.

Another attractive candidate process for OTEC plants is the electrolytic reduction of alumina (made from bauxite on shore) to aluminum. This process is an electric-power-intensive process requiring approximately 8 kWh/lb of aluminum. One 500-MW$_e$ plant could make 232,000 tons/yr (at a plant load factor of 0.85 and 8 kWh/lb of aluminum), or about 4% of the current U.S. production rate. At a delivered price near $800/ton, the value of the aluminum produced would equal the plant investment cost in about three years.

[32] E. A. Harre, O. W. Livingston, and J. T. Shields, "World Fertilizer Review and Outlook," TVA Report #TA(AO)6-69, 1974, National Fertilizer Development Center, Muscle Shoals, Ala.

Use of aluminum in automotive vehicles and trains can be expected to increase as efforts continue to reduce vehicle weights in order to reduce fuel requirements. Part of the market for the aluminum might be for subsequent OTEC plants. A 500-MW$_e$ OTEC plant with aluminum heat exchangers and some aluminum structure will require between 10,000 and 100,000 short tons of aluminum. (The low value is based on CMU estimates for heat exchangers using small fluted tubes; the high value, for use of plain, large-diameter tubes and some ship structure for plants in the tropics.) One tropical OTEC plant could reduce enough alumina for two to six or more plants (including portions of platform structures) of the same size every year. Aluminum also could be used to great advantage in solar collectors for the heating and cooling of buildings and for structures of other types of solar-energy plants. The main interface problem for an ocean-based aluminum plant will be to assure a steady supply of alumina (from bauxite). Use of suitable tropical sites such as Guam for near-shore OTEC operation would appear attractive.

Since magnesium chloride is a constituent of sea water, magnesium could be produced at sea by shipping calcium oxide (from oyster shells or limestone) to the platform, or getting it from the ocean floor. The demand for magnesium today could be met by just two 500-MW$_e$ OTEC plants. However, magnesium is superior to aluminum for many applications, and demand for it would rise and relieve requirements for other metals if its price became more competitive.

Another possibility for the late 1980s would be to ship coal or a carbonate to the platform and use the gaseous H_2 produced there to make synthetic oil, methane, or methanol. Although recent forecasts of coal liquefaction plant costs appear to make this possibility less attractive than production of ammonia or liquid hydrogen (LH_2), it warrants further evaluation.

For the longer term, the production of LH_2 for shipment to U.S. and foreign ports as a fuel is expected to be attractive. The estimates shown in Table 5 suggest a delivered cost of $4 to $5/10^6 Btu, which is below the present cost (above $10/10^6 Btu). It also is lower than the cost of gaseous H_2 produced by electrolysis using the fossil-fuel or nuclear plants in Table 1, or by thermal decomposition using nuclear energy in the 1980s if

Table 5

COST ESTIMATES FOR PRODUCING LIQUID HYDROGEN (LH_2) AT A TROPICAL OTEC PLANT AND SHIPPING 3000 MI. TO PORTS

Plant costs, \$/kW$_e$:		
Basic OTEC plant	357	
Electrolysis plant	60	
Hydrogen liquefaction plant	60	
Plant cost subtotal	477	
Add 12% for interest and escalation during construction	57	
Total plant cost, \$/kW$_e$	534	
Costs for LH_2 in \$/10^6 Btu by conventional (13% fixed charges) financing and ExIm Bank (10% fixed charges)*	Conventional	ExIm Bank
Fixed charges at 0.9 use factor	3.78	2.91
Operating cost†	0.56	0.56
Shipping cost	0.50	0.50
Cost at port, \$/10^6 Btu	4.84	3.97
Equivalent gasoline cost, \$/gal††	0.56	0.45

* Basis: Electrolysis plant operates at 85% efficiency to produce GH_2 at 3000 psia; liquefaction plant, at 80% efficiency; 1.47 kW$_e$h from plant are needed for each kW$_t$h of LH_2 produced.

† Equivalent to 1.3 mills/kW$_e$h of power required.

†† Not including taxes, storage and distribution costs, and profit on shore; energy content of gasoline, 115,000 Btu/gal.

nuclear plant costs keep rising. Such a cost for "clean" hydrogen fuel produced via solar energy also would be attractive compared to an equivalent gasoline-cost-at-the-refinery (see bottom line in Table 5). By 1990, much of the fossil fuel use in the U.S. probably will be based on coal and coal derivatives. Since the cost of U.S. coal probably will continue to rise, the costs of oil and gas made from it on shore may then exceed the cost of LH_2 made by a tropical OTEC plant. The use of LH_2 from an OTEC plant to liquefy coal on shore is another possibility but at present does not appear to be competitive. The use of LH_2 in fuel cells on shore (for which some sources now forecast capital costs below \$100/kW$_e$) to produce electric power also warrants study. However, its direct substitution for oil or coal in conventional steam-electric power plants does not look economical.

When LH_2 is delivered by tankers for subsequent use as a gas (GH_2), facilities at deep-water ports will be needed to transfer and store it at least long enough to vaporize it at a rate needed to match the requirements of a domestic GH_2 pipeline system. Each storage/vaporizing facility should be interfaced with a local commercial complex that can use the large resulting refrigeration capacity in order to recover the cost of the transfer and storage facilities. The GH_2 pipeline system will require more compressor substations than present natural gas pipelines, and burners of all types will require some modifications to use GH_2 exclusively, but nearly all burners can use a mixture of H_2 and natural gas (or low Btu gas from coal—the cheapest synthetic gas) with no modification. By the late 1980s, LH_2 facilities for automotive fueling could be available in many U.S. cities near the coasts if planning is begun soon, in which case the LH_2 delivered by tanker could be transferred directly to truck or rail tank cars for delivery to such facilities. In the 1990s fueling of aircraft by LH_2 could begin.

The foregoing estimates of costs of energy-intensive products made at OTEC plants remain speculative because of the lack of hard data. However, we concur with the other major investigators of OTEC plants that engineering feasibility is assured, and we believe that economically competitive production of ammonia at sea could begin as early as 1982 if given high priority support.

Potential Growth Rate for Tropical OTEC Plants

The current U.S. energy requirement is approximately 80×10^{15} Btu/yr or 80 Q/yr (1 Q = 1 quadrillion Btu). Most projections anticipate that this amount will at least double, to 160 Q/yr, by the year 2000. Tropical OTEC plants ultimately could provide many times this U.S. energy requirement.

Many participants at the Third OTEC Workshop[13] considered ammonia to be the most attractive candidate for initial production at sea. When demands for ammonia, aluminum, and other energy-intensive products previously mentioned have been alleviated by tropical OTEC plants, the nation may be ready to enter a "hydrogen economy" such as we just described. In a broad sense the industrial/resource/technological limitations on rate of growth of tropical OTEC energy production will be imposed not by the basic solar energy resource but by:

1. The ability to obtain the needed raw materials (e.g., bauxite for making aluminum) and/or metals for making the heat exchangers (mostly aluminum), turbines (aluminum and/or steel), generators (steel and copper), and platforms (alu-

minum, steel, and concrete). (Note again that no raw materials other than seawater and air are needed to produce ammonia at sea, except for periodic replacements of electrodes and KOH in the electrolysis cells and catalyst in the ammonia synthesizer.)

2. The ability to provide the manpower and construction facilities required to build the platforms (in shipbuilding facilities) and components (but no appreciable requirement for expansion is expected until the rate exceeds the order of six to ten plants per year of 500-MW_e size).

3. The ability to provide trained, seagoing engineering/construction crews and towing tender ships to accomplish the overall plant erection and startup process at sea.

4. The ability to attract operating crews for the plants and to provide support facilities on shore for crew training and for resupply and replacement operations.

According to Ref. 29, the achievement of 200 GW_e capacity by the year 2000 would correspond well with the expansion rate (lower curve slope in Fig. 15) for nuclear plants in the 1965–1980 time period derived from licensing, construction and planning information. However, approval and construction of OTEC plants, which would be offshore and are expected to have no appreciable environmental effects or safety hazards, could proceed even faster, so that the upper curve slope in Fig. 15 seems reasonable.

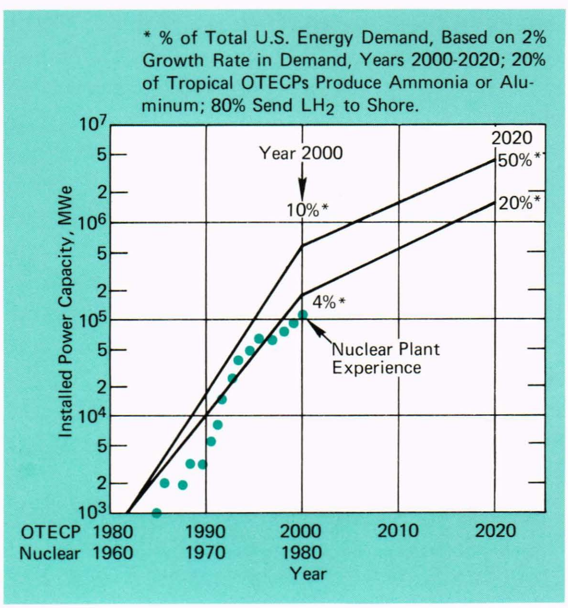

Fig. 15—Potential expansion rate and U.S. market capture for Ocean Thermal Energy Conversion Power Plants. (Reference data for nuclear plants from Ref. 29.)

Net Energy Assessment

A very important aspect of costs and socioeconomic values of future methods of meeting our energy requirements has been addressed by the Lockheed team, who stated:[16]

> Economic evaluations of alternative energy systems traditionally have been based upon the capital cost of establishing the plant and the operating cost of producing the power. Nonmonetary considerations involving plant construction and the dissipation of nonreplenishable resources were generally ignored. The growing concern for the environmental impact of most human activities has led to the realization that all proposals for the expenditure of resources can best be compared on the basis of energy used versus energy produced, as illustrated [in Ref. 33]. The energy used is the sum of the fuel used to run the power system (primary resource) and the energy resources consumed in the production of the systems required to supply the external energy input to operate the power system (external resource). The OTEC values calculated are compared to values for the other power systems [(adapted from Ref. 33) in Table 6]. OTEC yields a net contribution of useful energy to the environment (as do other direct solar-energy systems). In fact, it delivers more than five times the energy expended in its construction and operation. Clearly, it minimizes the demands upon nonrenewable fuels. Savings in fossil fuels could not only prolong their use for power generation by conventional plants, but could make them available also for other major uses such as the production of petrochemicals.

Suggested Implementation Plan for Tropical OTEC Plants

1. Complete initial experiments and design studies for tropical ocean plants during 1976, and design, build, and operate a 10-MW_e tropical plant in 1978.

2. Complete data gathering for all areas relative to plant operational viability, environmental impact analysis, etc., by 1978, in parallel with the foregoing item.

3. Complete detailed design of an optimum-sized (100 to 500 MW_e) tropical, OTEC-ammonia plant by 1979, and deploy it by 1981.

[33] Office of Energy Research and Planning, Office of the Governor, State of Oregon, Salem, *Energy Study Interim Report*, July 26, 1974.

Table 6

NET ENERGY COMPARISON (IN BTU) OF MAJOR ELECTRIC POWER GENERATION CANDIDATES (BY THE LOCKHEED TEAM[16])

System	*Energy Output*	−	*Primary Resource*	−	*External Resource*	=	*Net Energy*
OTEC	1000	−	0	−	145	=	+ 855
Nuclear	1000	−	7425	−	451	=	−6876
Coal-Fired	1000	−	3498	−	566	=	−3064

4. Have a number of additional plants producing ammonia or other products by 1985. Include European or other participation to assure economic and political viability and safety of these tropical plants.

5. Move onto exponential expansion curve to have 210 to 640 GW_e total capacity (4% to 10% of U.S. total energy demand) in operation by the year 2000.†

Conclusion

The engineering feasibility of closed-Rankine-cycle, ocean thermal energy conversion (OTEC) plants has been assessed by many independent investigators in recent years. Engineering development is judged by the writers and several other groups to be a straightforward task that can be accomplished essentially as rapidly as funding permits. Component demonstrations, especially heat exchanger tests to provide design data for cost-effective approaches (including handling of a possible biofouling problem) are needed promptly, to be followed rapidly by pilot/demonstration plant construction and operation.

Because the OTEC resource—solar energy via ocean temperature differences—is most attractive within 10° latitude of the equator, production of energy-intensive products at sea to relieve fuel or electric power demands within the U.S. is attractive. Ammonia production at sea, to fill needs for fertilizer while relieving natural gas demands, looks economically competitive now and could begin by 1982 with adequate support. The possibility of direct delivery of electric power to U.S. utility grids from plants off the lower U.S. East Coast and in the Gulf of Mexico could supplement the suggested implementation plan for tropical OTEC plants that has been presented.

† Based on meeting all U.S. ammonia needs, with 5%/yr increase in demand for ammonia, 1985 to 2000 (25×10^6 ton/yr in 1985), and all U.S. aluminum needs, with 3%/yr increase in demand, 1975 to 2000. The remainder would be used to produce 2.65 Q_t in LH_2 (at 68% efficiency) in the year 2000 for the total 7.2 Q_t level (4% of total U.S. energy demand) or 11.45 Q_t in LH_2 for the total 16 Q_t level (10% of total U.S. energy demand).

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