Floating Ocean Thermal Power Plants and Potential Products

G. L. Dugger, H. L. Olsen, W. B. Shippen, E. J. Francis, and W. H. Avery
Applied Physics Laboratory, The Johns Hopkins University, Laurel, Md.

ENORMOUS amounts of energy may be derived from the sea by exploiting the temperature difference between the upper water layer heated by the sun and the deeper cold layer returning from arctic regions, as d'Arsonval pointed out in 1881. Half a century later, George Claude[1] operated the first crude ocean thermal difference power plant at the edge of Matanzas Bay, Cuba. He laid a 1.6-m-diam by 1.75-km-long cold-water pipe from the shore into the bay, reaching a depth of 700 m. From a sea-water temperature difference of 14°C, his turbine and generator developed 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.) By 1981, many investigators believe, an ocean thermal energy conversion (OTEC) demonstration plant of 25 to 100 Mw_e size, probably based on the closed Rankine cycle process, rather than the open-cycle process demonstrated by Claude, could be in operation.

Let us briefly describe the two processes at this point. In Claude's open-cycle process, Fig. 1, 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 sea water, drawn from 700-m depth, which fell like rain in another evacuated chamber used as the condenser. Improvements to Claude's design have been described, e.g., by Walters[2] and Brown and Wechsler.[3] The primary concern has been the very large turbines required because of the very low steam pressure (0.03 atm), but Brown and Wechsler[3] do not believe such turbines need to be expensive. They mention an analogy to helicopter rotors, as far as size goes, and suggest a light-weight blade construction similar to sailplane wings. Development work also would be needed on the direct-contact condensers.[3] The writers have

---

Gordon L. Dugger, Assistant Supervisor of the Aeronautics Division and AIAA Fellow, received a Ph.D. in chemical engineering (1953) from Case Institute of Technology. He conducted combustion research at the NACA Flight Propulsion Laboratory (1947-54) and supervised chemical process research for International Minerals and Chemical Corp. (1954-57). At APL he has supervised advanced ramjet, air-augmented rocket, and scramjet propulsion R&D. He was AIAA Vice President-Publications, 1970-74.

H. Lowell Olsen, a Principal Staff Physicist and AIAA Member, received a Ph.D. in physics (1949) from the University of Wisconsin. He was an NACA research scientist (1940-46) and an instructor at the University of Wisconsin (1946-49). At APL he conducted combustion research and developed and supervised the Propulsion Research Laboratory prior to his present assignment in the Aeronautics Division Office. He is Principal Investigator on the APL project on two-phase flow heat exchangers for ocean thermal plants for the ERDA Division of Solar Energy.

William B. Shippen, Supervisor of the Propulsion Group and AIAA Associate Fellow, received a B.S. in mechanical engineering (1940) from the University of Virginia. He worked on aircraft subsystems for The Martin Co., 1940-48. At APL he supervised ramjet engine development for the Navy's Talos and Typhon LR missiles and now supervises air-breathing engine development and the Propulsion Research Laboratory. He has served on the AIAA Air-Breathing Propulsion Technical Committee.

Evans J. Francis, Executive Assistant for the Aeronautics Division and to the Assistant Director for Exploratory Development, received an M.B.A. (1961) from George Washington University. In the U.S. Navy (1950-70) Ensign to Commander, he worked in comptroller, logistics, data processing, and computer applications. At APL he was Executive Assistant for the Computing Center (1970-74). He is Principal Investigator on the APL study of maritime aspects of ocean thermal plant-ships for the U.S. Maritime Administration.

William H. Avery, Assistant Director of APL for Exploratory Development and Director of the Aeronautics Division and AIAA Fellow, received a Ph.D. in physical chemistry (1937) from Harvard University. He was a research chemist for Shell Oil Co. (1939-43) and Head of the Propulsion Division at the Allegany Ballistics Laboratory (1943-47). At APL he held numerous positions directing research and development in propulsion, energy, and related areas. He has served on many DOD, NACA, NASA, and NAS committees. Among his awards are a Presidential Certificate of Merit, the AIAA Hickman Award, and a Combustion Institute Gold Medal. He chaired the ARS Ramjet Technical Committee and was an AIAA Director, Technical (1968-71).

Presented as Paper 75-617 at the AIAA/AAS Solar Energy for Earth Conference, Los Angeles, California, April 21-24, 1975; submitted May 5, 1975; revision received July 14, 1975. The authors prepared this paper under an IR&D program of the Applied Physics Laboratory of The Johns Hopkins University. Contract N00017-72-C-4401 with the Department of the Navy. Contributions to the plant design concepts and corresponding cost estimates were provided by R.W. Blevins, V.J. Dietz, A.S. Polk, P.P. Pandolfini, J.L. Keirsey, and others at APL/JHU. In addition, major portions of the material have also been used in Chapter 10 of the AIAA assessment of "Solar Energy for Earth," and Helpful comments of the first draft of that chapter were received from R. Cohen of the Solar energy Division of ERDA, C. Zener of the Carnegie Mellon University, W.E. Heronemus of the University of Massachusetts, J.H. Anderson Sr, of Solar Sea Power, Inc., R.H. Douglass of TRW Systems and Energy Group, TRW, Inc., and L.C. Trimble of the Lockheed Missiles and Space Company, Inc., as well as J. Grey of the AIAA staff.

Index categories: Electric Power Generating Research; Marine Electric Power Systems; Marine Vessel Systems, Submerged.

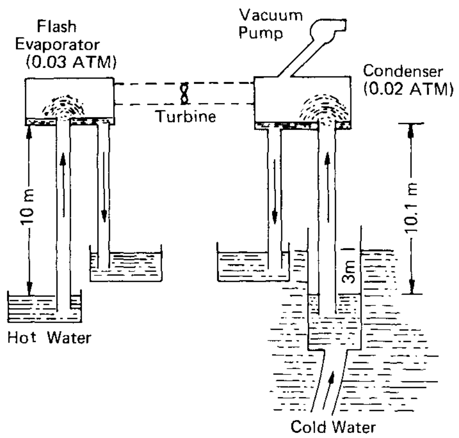

Fig. 1 Claude's basic open-cycle scheme for ocean thermal energy conversion. Flash-evaporated sea-water drives a turbine and is then recondensed by cold water falling like rain in the condenser.

heard that some research efforts on new approaches on the latter have begun but are as yet unpublished.

In contrast, in the closed Rankine cycle a working fluid such as ammonia is evaporated and recondensed in heat exchangers by warm and cold sea water, respectively (Fig. 2). Using ammonia, the turbine inlet pressure will be 8.7 atm, and consequently the turbines will be smaller by two orders of magnitude.

In the 1960's J. Hilbert Anderson and James H. Anderson Jr. espoused the virtues of "sea solar power" using the closed Rankine cycle.[4-7a] At the first National Science Foundation (NSF) Workshop on the subject in 1973,[7] they announced the formation of their company, Sea Solar Power, Inc. At that meeting, the University of Massachusetts group headed by Heronemus and McGowan,[7b,8-12] and the Carnegie-Mellon University (CMU) group headed by Zener and Lavi[7c,13-16] (who had received grants from NSF for OTEC studies), as well as the writers[7d] and several others, shed further light on the feasibility and prospects for development of OTEC power derived from solar energy via the closed cycle. The long-term French interests were represented by Barnea,[7e] who advised that the open-cycle process be kept in the picture. However, the remainder of this survey will be addressed to the closed-cycle (Fig. 2) process.

At the second NSF OTEC Workshop in 1974,[17] it was announced that Lockheed Missiles and Space Company, teamed with Bechtel Corporation, and TRW Systems Group, TRW, Inc., teamed with Global Marine Development, Inc. and United Engineers and Constructors, had received system study grants from NSF. In January 1975, the Energy Research and Development Administration (ERDA) was formed, and the majority of OTEC work was transferred from NSF to ERDA (Robert Cohen, Division of Solar Energy). In May 1975, the 3rd OTEC Workshop[18] featured the aforementioned system study reports* by the Lockheed team headed by Trimble[18a] and by the TRW team headed by Douglass.[18b] Thirty-one other papers were presented, including brief reports on planned work on 16 new projects for ERDA,[18e-t] four for NSF/RANN,[18u-x] and one for the U.S. Maritime Administration (MARAD).[18y] The new ERDA and NSF awards covered numerous aspects of heat-exchanger research including biofouling and corrosion aspects, platform and mooring-system studies, energy delivery/use studies, site studies, environmental impact studies, and legal aspects, as the titles[18c-x] denote. Beyond that, Cohen[18z] noted that NSF had received another 64 proposals under the 1974 NSF/RANN Program Solicitation No. 74-9. The MARAD contract to the writers is for investigation of the maritime aspects of tropical-ocean plant-ships producing ammonia or other products. The NOAA Office of Sea Grant has supported work on OTEC platforms.[18dd]

*Portions of the Lockheed[19] and TRW[20] system studies were presented at the OTEC session of the AIAA/AAS Solar Energy for Earth Conference, April 1975, at which most of the present survey material (AIAA Paper 75-617; see also Refs. 21 and 22) was presented, and the Offshore Sources of Energy Session at the Offshore Technology Conference, May 1975.[23]

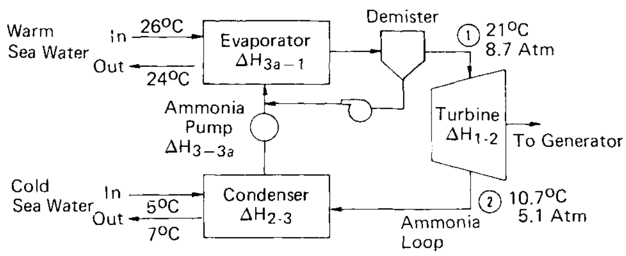

Fig. 2 Simplified loop diagram (for tropical ocean temperatures and ammonia working fluid) for the closed-Rankine cycle, Ocean Thermal Energy Conversion (OTEC) plant.

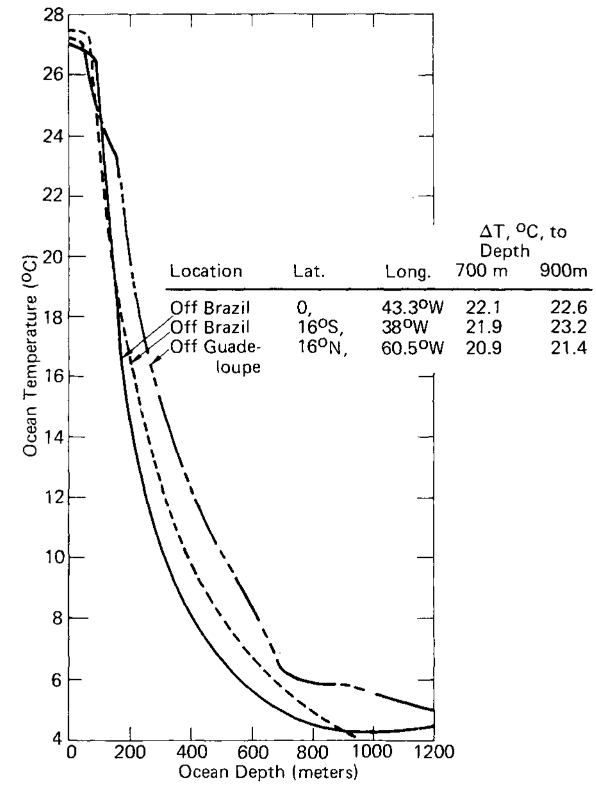

Fig. 3 Thermoclines in the tropical Atlantic Ocean (from data in Ref. 24).

This recent rapid growth in programs and proposals (representing in-house support) from academic, industrial, and government-laboratory quarters attests the widespread confidence today that delivery of OTEC power to shore and its use to make energy-intensive products at sea, do indeed look promising as near-term means of alleviating the nation's energy and balance-of-payments problems.

The Source to be Tapped

Oceans cover 71% of the earth's surface. They constitute a natural solar energy collection and storage system, and the resulting thermal energy can be drawn off 24 hr/day by OTEC plants. The tropical oceans are particularly attractive. Temperature differences of 20-23°C or more between the surface and the depths are available, as illustrated in Fig. 3. Furthermore, in the region between 10°N and 10°S, an OTEC plant-ship can navigate to stay in regions where: winds do not exceed 25 knots; there are no hurricanes; and currents are below 1 knot at all depths. Thus, construction and maintenance of plants designed to "graze" in this region would present minimal problems.

The available ocean area in the ± 10° latitude band is about 80 million km² (30 million miles²), and it receives a 24-hr-average solar energy flux in excess of 215 w/m², or 1.7×10^{10} Mw_t total. Floating OTEC plants would need to develop electric power equal to only 0.004% of this incident solar energy in order to equal the projected U.S. electric power demand in the year 2000.

Because much of the tropical ocean belt is remote from the U.S., locations in the Gulf Stream off the lower U.S. east coast[12,18c] in the Gulf of Mexico,[14] off Puerto Rico,[18u] and off Hawaii[18cc] are also being studied. A significant fraction of the power required by the southeastern states could be provided by moored OTEC plants with undersea cables to shore. However, the available ocean temperature difference in the Gulf Stream is 20%-30% smaller than in the tropics, and much sturdier construction will be needed to withstand the large currents and frequent hurricanes. Thus, the costs of construction and maintenance of such plants have to be weighed against the costs of getting the energy to shore by other means from less expensive tropical plants, or using the power at sea to produce ammonia (for fertilizer) or liquid hydrogen (for many uses, e.g., Ref. 25), or other products.

At this point let us mention ocean tidal power for comparison (see, e.g., Ref. 26). Power can be extracted from tides by filling and emptying a dammed coastal bay or estuary during tidal periods. A 240-Mw_e plant on the Rance River in France is producing 544 million kwh/yr, achieving a load factor of 0.26, in a contrast to the 0.9 load factor projected for OTEC plants. Only one location in North America has aroused serious interest—the Bay of Fundy-Passamaquoddy Bay area between Maine, New Brunswick, and Nova Scotia, where 15-m tides exist. If the system designed in 1961 were built at the estimated cost of \$3400/kw_e average power delivery (1961 dollars), it would provide only as much power as a single 230-Mw_e OTEC plant. This high cost and small potential make tidal power of little interest to the U.S. There is a greater potential on the northern coasts of the U.S.S.R., but it is still miniscule compared to the worldwide potential of ocean thermal power.

Detailed comparisons of OTEC potentials with those of other systems that develop power from solar energy[21] are beyond the scope of this paper, but OTEC systems have far greater economic promise than photovoltaic (solar cell) power systems. Biomass energy systems, and possibly wind-power and direct-solar-thermal-power systems, may prove competitive but will lack by far the quantitative resource potential that exists for OTEC power. However, a possible synergistic payoff worth noting is the combination of a floating biomass farm (and/or possibly a fish/shellfish farm) with an OTEC plant.

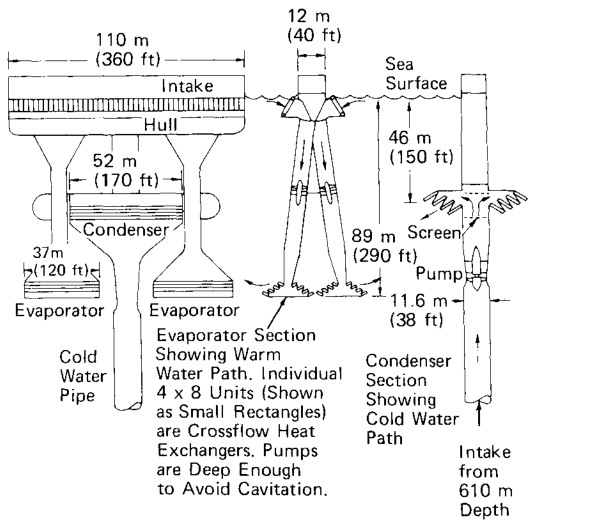

Fig. 4 The Andersons' 100-Mw_e, closed-cycle OTEC plant concept using propane as the working fluid. All pumps are driven by propane turbines inside the pump hubs.[5]

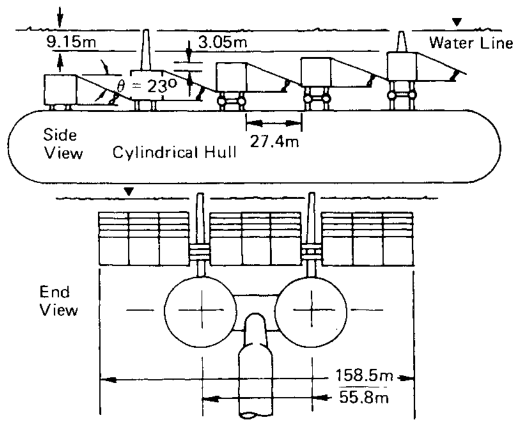

Fig. 5 The 400-Mw_e, submerged-catamaran configuration "Mark II" Ocean Thermal Energy Conversion (OTEC) plant design by the U. Mass. for use in the Gulf Stream off Miami, Florida.[11]

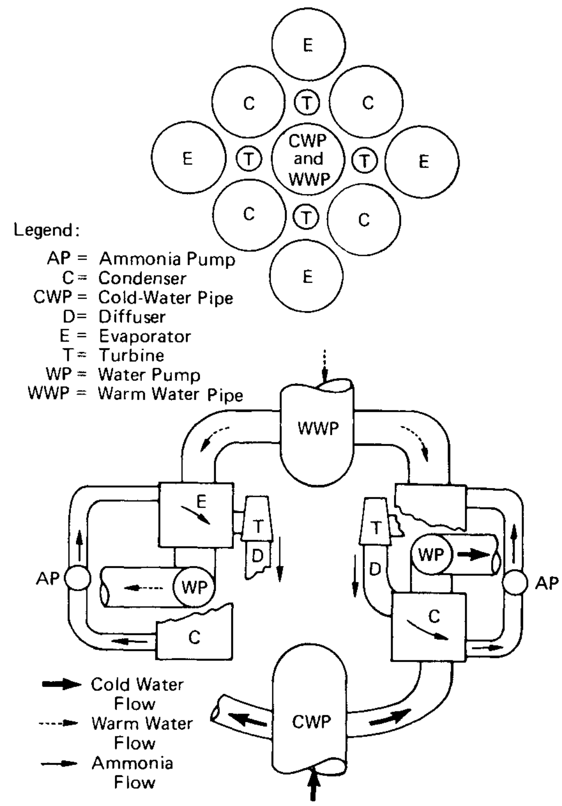

Fig. 6 Carnegie-Mellon University's modular scheme for a fully submerged, unmanned plant. The warm water (WWP) inlet (with screen) is near the surface; the cold water (CWP) inlet (with screen) is at 500-700 m depth.[13]

Conceptual Design for OTEC Plants

Anderson and Anderson

In 1966, Anderson and Anderson[5] presented a conceptual design for a 100-Mw_e OTEC plant (Fig. 4) and estimated a capital cost of \$167/kw_e of power capacity, a cost competitive then with fossil-fuel plants. Some of the features of their concept are of continuing interest: a) a floating platform supports the plant, and an analogy to stable platforms for deep-hole drilling was mentioned; b) the evaporators and condensers are submerged; and c) the working fluid is propane, whose high working pressure permits use of efficient, low-cost, single-stage turbines. (Later they switched to a Freon-class fluid, R-12/31.)

University of Massachusetts

More recently, Heronemus et al.[8-12] designed submerged catamaran configurations to be anchored in the Gulf Stream off Miami, Florida. In their "Mark II," 400-Mw_e plant concept (Fig. 5), the turbines and plate-fin condensers are housed in twin 24-m (80 ft)-i.d. × 183-m (600-ft)-long concrete hulls. Banks of plate-fin evaporators are staggered in depth serially above the hulls to take advantage of the Gulf Stream current to reduce the pumping work. The cold-water pipe, hinged from a header between the hulls as shown in the end view, would extend to a depth near 300 m (1000 ft). An undersea cable would take the power to shore.

Carnegie-Mellon University

Zener and Lavi[13-16] propose an unmanned, automated, submerged plant having multiple power modules (Fig. 6).[14] They have devoted more attention to geometric programing to find optimum component designs, especially for fluted-tube heat exchangers.[12]

Applied Physics Laboratory, JHU

A tropical-ocean, OTEC plant-ship concept to which APL has devoted limited study under an IR&D program and the beginning of the MARAD contract mentioned earlier is illustrated in Fig. 7. It has a 62-m (196 ft) beam, a length of approximately 145m (476 ft), and a displacement of approximately 55,000 metric tons. Large banks of submerged condenser modules are located fore and aft of the central cold-water pipe, which extends to 750-900m (2500-3000 ft) depth. Large banks of submerged evaporator modules are located outboard of the condensers. Advantages APL sees for use of relatively small power modules (order of 5 Mw_e) and of relatively large diameter tubes (6-9 in.) in these two-phase-flow heat exchangers are discussed later. The exit flows from the evaporators and condensers could be directed to assist in the station-keeping needed in the mild 0.5-knot currents in which the plant is intended to operate.

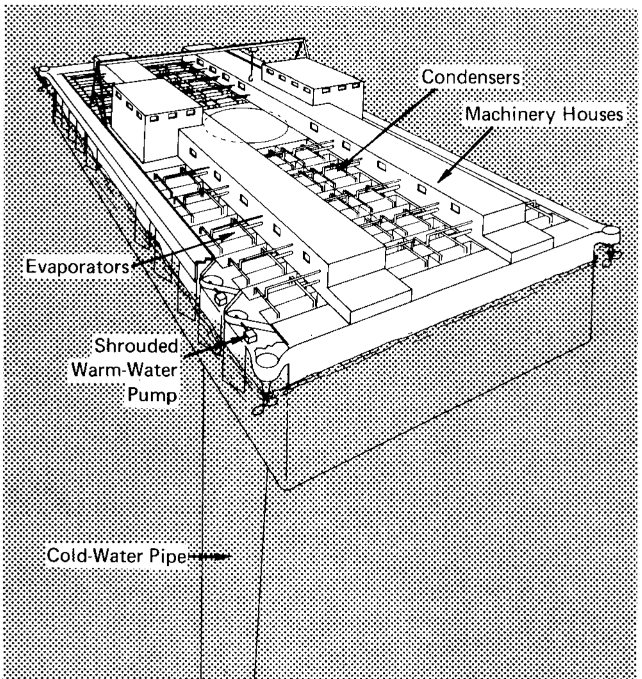

Fig. 7 An APL/JHU concept for an OTEC plant—the cold-water pipe brings water to the central well to flood banks of multi-module condensers in the deck openings nearest it. Four banks of multi-module evaporators are located in the outermost deck openings, with warm-water pumps in the outboard shrouds.

Lockheed, Bechtel Corporation, and T. Y. Lin International

The baseline plant design that evolved from this team's 9-month (July 1974-April 19 ,) OTEC system study[18a,19,23a] for

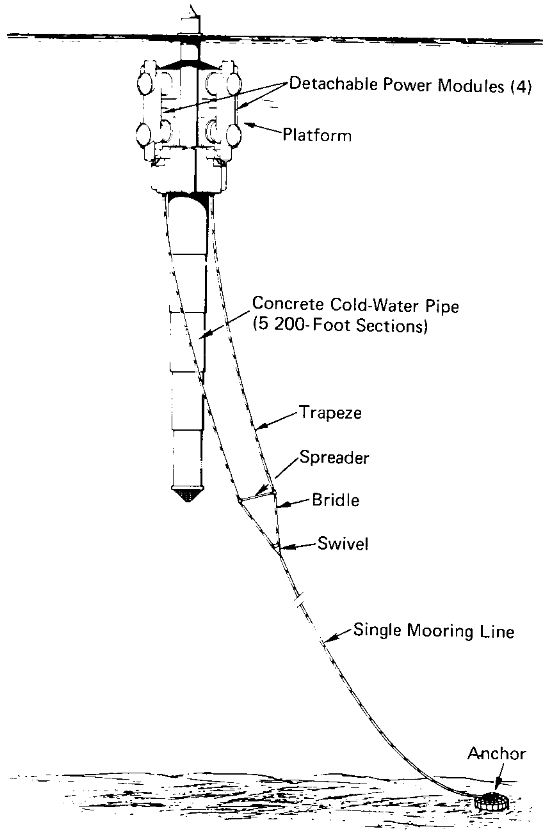

Fig. 8 The moored, spar-buoy type, 160-Mw_e plant design concept of the Lockheed/Bechtel Corporation/T. Y. Lin team.[18a]

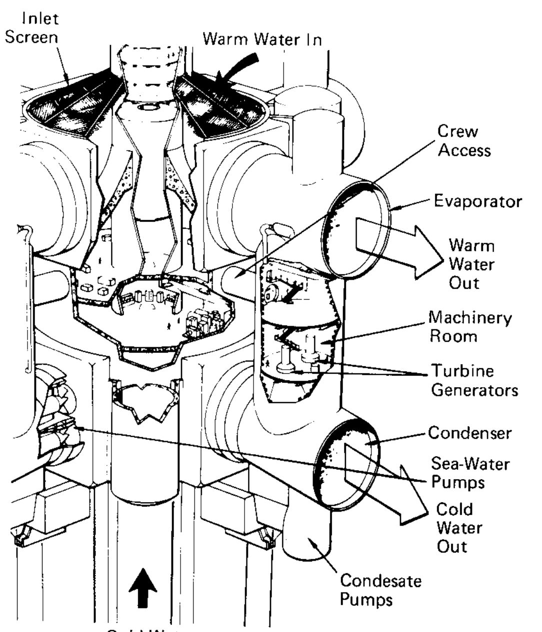

Fig. 9 Close view of one power module (of four) in Lockheed's plant concept.[18a]

NSF/RANN is a spar-buoy configuration, primarily of reinforced concrete construction, with a telescoping, concrete cold-water pipe reaching 1500-ft depth (Fig. 8). Its displacement is approximately 300,000 tons. In his talk, Lin[23a] provided many examples of large, reinforced concrete structures that have demonstrated the necessary technology in that area. Four detachable power modules (Fig. 9) using titanium-tubed heat exchangers, with sea water inside and ammonia outside the tubes, generate a total net output of 160 Mw_e. The plant is designed for use in virtually any appropriate location in semitropical or tropical waters with a 100-yr system life expectancy (even in the hurricane belts) and to maintain a consistent value of thermal efficiency.

TRW Systems, Global Marine, and United Engineers and Constructors

This team, who was also just completing a 9-month study for NSF/RANN, reported[18b,20,23b] that it had briefly investigated three spar-buoy configurations, six semisubmersible configurations, and six surface vessel configurations before selecting the cylindrical surface vessel configuration shown in Fig. 10 for their baseline design effort. It is 343 ft in diameter and has a displacement of 213,000 tons. Four power modules located within the reinforced-concrete hull, which includes room to work on them, generate 100 Mw_e net output. As in the Lockheed baseline design, the heat exchangers use titanium tubes with ammonia working fluid outside the tubes. However, the TRW plant design includes a cold-water pipe made of fiber-reinforced plastic with a length of 4000 ft to achieve a higher ΔT for the plant, and they judge that a dynamic plant 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, especially for use in tropical oceans. The plant is designed for 40-yr life.

Bottom Condenser not Practical

It is often asked why the condenser should not be put at depth and the large cold-water pipe eliminated. The answer is 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 sea water up; and b) the condenser would have to be much heavier and costlier to withstand the hydrostatic pressure at depth.[11]

Prospects for Successful Plant Designs

In summary, a number of approaches to the overall design of an OTEC plant may be acceptable. Design differences for application in tropical oceans vs the Gulf Stream are to be expected, just as designs for off-shore drilling platforms vary for different environments. Additional studies are in progress.[18] Tradeoff studies, based on additional experimental data that will be obtained in the next year or two, will determine the most cost-effective configurations, but the various investigators to date have not encountered any formidable problems. The industrial teams, the university teams, and the writers concur that prospects for economically competitive ocean power plants look very good. State-of-the-art solutions to remaining problems can be made.

Turbine Technology for OTEC Applications

Several investigators concur that either ammonia or propane turbines should best be single-stage machines of 50 Mw_e capacity or less. We see possible advantages in going to turbines as small as 5-10 Mw_e in order to capitalize to the fullest extent on plant modularization and repairability of low-cost heat exchangers.

Turbine design will be relatively straightforward. Figure 11 (from Anderson[7b]) shows where all known turbines fit in

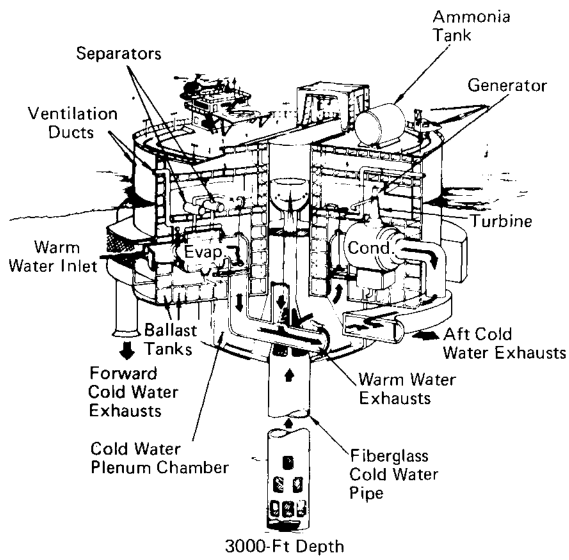

Fig. 10 The floating, cylindrical-surface-vessel, 100-Mw_e plant design concept of the TRW/Global Marine/United Engineers and Constructors team.[18b] Shrouded-pipe water jets (condenser discharge) control the plant position.

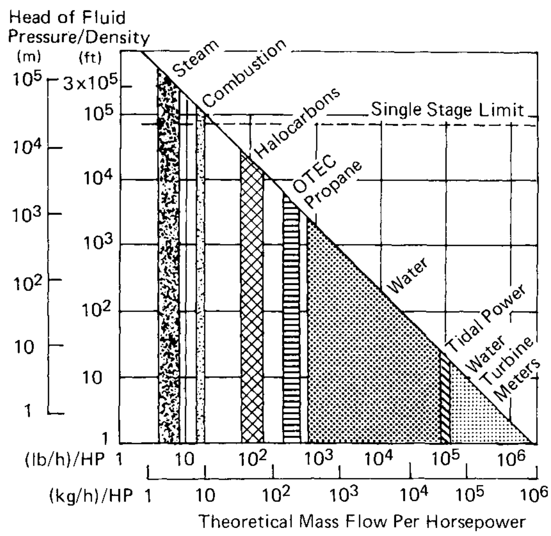

Fig. 11 The spectrum of turbines.[7b]

terms of heat (m or ft) vs theoretical mass flow per horsepower obtained, from the ordinary, high-pressure steam turbine that produces heads near 90,000 m (300,000 ft) at low mass flow per horsepower, to the water turbine meter which operates with heads as small as 0.3 m (1 ft). The turbines for OTEC plants will fall between the hydroelectric water turbines and combustion gas turbines.

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. It should be possible to select a specific design point with a high efficiency (near 90%) without concern for operation over a broad rpm range, because load adjustment for the OTEC plant can probably be done by cutting out one turbine at a time.

Figure 12 shows estimates[27] of turbine characteristics and costs (\$/kw_e of net output, in 1973 dollars, taking into account a 33% parasitic pumping power penalty) for a Gulf Stream plant (32°F temperature difference) based on a 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 (Fig. 12a) and

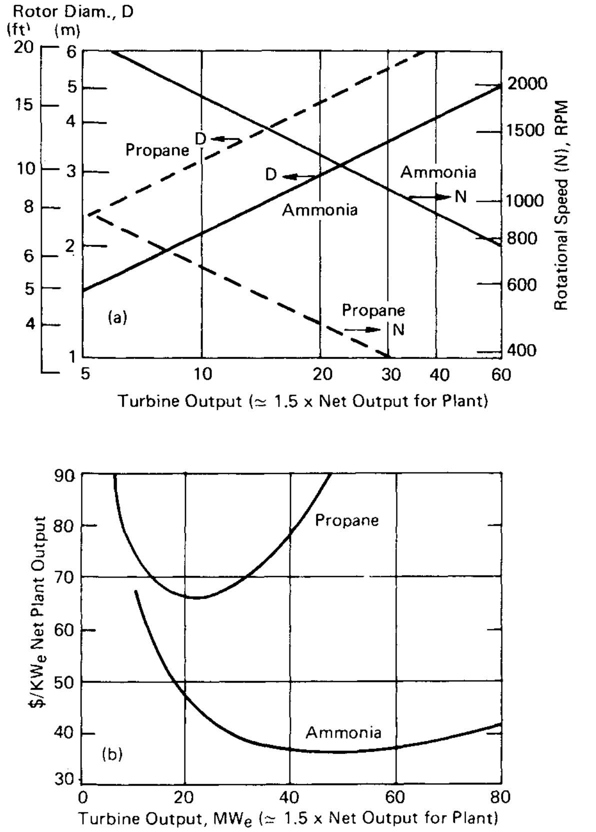

Fig. 12 Turbine characteristics and cost estimates for propane and ammonia working fluids for an OTEC plant in the Gulf Stream.[27]

cost nearly twice as much (Fig. 12b). Transportation and installation costs would add 25-30% to these figures. Since plant efficiency varies with the ocean temperature difference (ΔT) raised to a power between 2 and 3, an increase in ΔT from 17.8°C (32°F) to 22.2°C (40°F) by going to a tropical ocean site could reduce the turbine cost by approximately 40%. Thus, the installed cost for near optimum ammonia turbines for a tropical site would be near \$30/kw$_e$ net in 1973 dollars.

Heat Exchangers

The evaporator and condenser will be the largest and most costly components on the basic OTEC plant. Selection of the most suitable design from the overall viewpoints of system engineering, first cost, and total lifetime costs will involve a number of factors:

a) 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.

b) 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.[7a,9] 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.[18b] Propane is next best thermodynamically, is noncorrosive, and has a similar working pressure range—80-150 psia—but its mass flow rate would have to be over 3 times as great. Freon would offer the advantage of nonflammability but would be still lower in performance.

c) In the evaporator 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 1.5 m/sec (5 fps) 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 sea-water side or preventing the biofouling (e.g., by adding 0.1-0.3 ppm of chlorine to the sea water either batchwise or continuously). Biofouling will be a smaller, perhaps negligible, problem in the condenser, because there will be far fewer organisms in the cold water drawn from great depths.[28]

d) Material selection will represent a compromise.[29-31] Most underwater structures 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. For the heat-transfer surfaces, the 90/10 copper-nickel alloy commonly used in marine condensers has excellent thermal conductivity. It is resistant to fouling, and could be used with propane as the working fluid, but it is expensive, is not compatible with ammonia, and the copper leached from it would have an adverse environmental impact. Titanium has excellent corrosion resistance except for galvanic corrosion, but it, too, is very costly. Aluminum, in suitable alloys which are practically inert to sea water[31] and are much lower in cost than Cu-Ni or Ti, has proven very satisfactory for heat exchangers for desalting plant use.[32] It also has very good thermal conductivity. Thus, an aluminum alloy would appear to be more cost effective for the heat exchanger tubes and may also be used for the shells.

e) Fins,[11] flutes,[15] or porous surfaces[33] may be used on the working-fluid side to enhance heat transfer rate, but probably will be impractical on the sea-water side, particularly in the evaporator, because they would make cleaning operations more difficult. If appreciable fouling does occur, its effect will dominate the overall heat transfer coefficient (U) and reduce the percentage gains in U due to surface enhancement.

f) Leak detection and repair (or module deactivation and replacement) must be possible and is an important factor in design of such huge exchangers. For this reason, and to reduce initial assembly costs, designing to reduce the number of tube joints may be more important than striving for maximum efficiency.

When all of the foregoing factors are weighed by obtaining the critical test data and conducting system engineering and socio-economic tradeoff evaluations with the benefit of such data, the most cost-effective, environmentally acceptable heat exchanger designs will emerge. The majority of system designers now appear to favor ammonia as the working fluid. We believe that aluminum should be used for the heat exchangers to minimize first cost and maximize the possibility of a quick payoff for early OTEC plants. Furthermore, we see the following potential advantages for simple, two-phase-flow heat exchangers using ammonia *inside* multipass (folded approximately 20 times), 6- to 9-in.-diam. aluminum tubes:

1) Although the required surface area will be increased somewhat with the larger-diameter tubes, the number of joints required will be greatly reduced, thus reducing the costs of fabrication, leak-testing, and inspection. Overall heat exchanger cost is expected to fall in the range \$1.50-\$3.00/ft^2 of heat transfer surface,† based on an estimated cost of 80¢/lb for fabricated aluminum tubing,[34] compared to \$9-\$12/ft^2 for shell-and-tube, titanium heat exchangers.[18a,b]

2) With the sea water flowing single-pass, outside (and parallel to) the multipass tubes, the "shells" will have sea water on both sides with very little pressure differential, so that they can have thin walls and rectangular cross sections to facilitate multi-modular arrangements. With this flexibility in module design, it should be possible to achieve an economical plant-ship platform design along the lines suggested by Fig. 7 to take advantage of the relatively benign, tropical-ocean environment. A multi-modular, low-draft (prior to cold-water

†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.

pipe installation) design is also expected to facilitate construction in existing U.S. shipyards. Since the heat exchangers themselves will be buoyant, the best overall structural arrangement for economy remains to be specified. The limited work that we have done to date with an integrated team including Sun Shipbuilding & Dry Dock, Hydronautics, Inc., The Woods Hole Oceanographic Institution, and Kaiser Aluminum and Chemical Corp. indicates that a good, economical design will emerge.

3) The use of 20 or more power modules in a total plant will permit a regularly scheduled cleaning operation, one module at a time, without appreciable reduction in power output.

The Cold Water Pipe (CWP)

Fabrication and development of the cold-water pipe (CWP) for an OTEC plant will be a challenging engineering/logistics problem, just as it was for Claude in 1930[1] and the French team who demonstrated CWP deployment for a 3.5-Mw_e (net) power plant off the Ivory Coast of Africa in 1956.[35] 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 12-18 m (40-60 ft) diam will be needed to pump approximately 8 million gpm of sea water through the condensers. These flow figures are based on an overall ΔT near 22°C with ammonia as the working fluid, and parasitic pumping power losses near 25% (133 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, the loss due to friction in the CWP and the dump loss from it to the condensers will range from approximately 4 Mw_e for a 15.3-m diam (3 m/sec or 10 fps water velocity) to 11 Mw_e for a 12.5-m diam (4.6 m/sec or 15 fps velocity). In comparison, pumping power required for the evaporator(s) and condenser(s) will be 6-10 Mw_e each, and for the head loss due to sea-water density change with depth in the CWP, ~4 Mw_e.

An APL preliminary analysis indicates that the buckling requirements for a CWP for a plant in the tropics, where currents are below 1 knot, can be met by an economical, double-walled aluminum structure. Others are studying, e.g., reinforced fiberglass[23b] and reinforced concrete,[23a] but the concrete design has not been evaluated for use for depths much greater than 1700 ft.

Cost Estimates for Power Production

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 costs of competitive systems have settled to some predictable pattern. Coal-fired plant costs have tripled in the past decade, and nuclear fission power plant costs have risen from \$200/kw_e to projections as high as \$1100/kw_e or more for plants that will come on line in the 1980s.

A simple comparison 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-\$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

Table 1 Approximate power cost comparisons for new construction to estimate allowable competitive cost for an OTEC plant[a]

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

[a]This must include the cost of getting the power to shore.
[b]Values from Ref. 36. Costs include \$100/kw_e for pollution and safety control costs, and costs for fossil fuel plants include 30-day fuel storage facilities.
[c]Oil at \$11/bbl and coal at \$28.50-\$37/ton. In September 1974 the TVA negotiated a contract with Webster County Coal Co. for 1.5 million tons/yr from 3 yr at \$28.50/ton, subject to price adjustment (*Energy Users Report*, Nov. 28, 1974). The Potomac Electric Power Company has paid \$37/ton (*Washington Post* article quoting PEPCO president, Nov. 11, 1974). Based on heat rate of 10,000 Btu/kwhr.

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.[37]

Table 2 compares capital cost estimates for OTEC plants from four sources: ours (APL/JHU), the Carnegie-Mellon University (CMU) group, who presented "low, medium, and high" estimates (medium shown here)[14] the Andersons' 1966 estimate[5] revised for estimated escalation to 1974 dollars, and the University of Massachussets (U. of Mass.) group.[12] For comparison, the estimate from U. Mass. for propane working fluid has been converted to use of ammonia in the last column. These various estimates are remarkably consistent when the strong effects of the sea-water ΔT and the working fluid are taken into account, although the Andersons' estimate remains more optimistic, especially on turbogenerator costs.

The cost estimates presented by the two industrial teams headed by Lockheed[18a,19,23a] and TRW[18b,20,23b] (subsequent to the initial preparation of this paper) are 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 sea water 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 \$1800-2000/kw_e by TRW (for a 40°FΔT) and \$2500-2600/kw_e by Lockheed (for a 34°F ΔT). Approximately 50% and 58% of these costs, respectively, are for the titanium-tubed heat exchangers, and both teams note that these heat exchanger costs could be reduced by 40-70% by improved designs based on aluminum. Both teams and the NSF and ERDA program offices also recognize the strong desirability of getting capital costs down for "*n*th 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 ΔT) that could ultimately lead to a heat exchanger cost as low as \$200/kw_e with sheet-metal construction.[19,23a] The TRW team notes that major cost reductions might be achieved in the plat-

Table 2 Estimates of capital cost, $\$/kw_e$ (in 1974 dollars) for OTEC power plants

Parameter	Source:	CMU[14]	APL/JHU[a]		Anderson[5]	U. of Mass.[12]	
	ΔT:	36°F	39°	43°	40°F	32°F	
	Site:	...	Tropics		Tropics	Gulf Stream	
	Fluid:	Ammonia	Ammonia		Propane[b]	Propane	Ammonia[c]
Evaporators, $\$/kw_e$		140	69	54	43	330	254
Condensers		140	84	66	43	63	63
Cold water pipe		58	45	40	20		
Turbogenerators		89	60	50	34		
Pumps		148	17	14	27	179	100
Working medium		9	2	2	<1		
Auxiliaries, piping, misc.		36	30	24	44		
Platform		36	50	43	72	48	48
Plant cost to busbar, $\$/kw_e$		656	357	293	284[b]	629	465

[a] APL estimates are based on the following values and approach: 1) $1.50/ft² of surface area for the aluminum heat exchangers. 2) $\$60/kw_e$ net plant output for turbine-generators with d.c. output when ocean $\Delta T = 39°F$. 3) $\$40/kw_e$ of pumping power for all pumps. 4) A low-cost platform similar in concept to Fig. 7. This approach is currently receiving more intensive analysis under a program begun in April 1975 for the U.S. Maritime Administration. Recent studies for offshore installations have led to costs considerably higher than the above numbers. In view of sharply escalating material and labor costs, firm estimates are not yet possible. These numbers were judged reasonable, based on 1973-74 quotes from suppliers, for plants in the benign tropical environment.
[b] Andersons' 1966 estimate[5] adjusted for inflation at an average rate of 5% per yr, 1966-72, plus 10% per year 1972-1974.
[c] Adjustment of U. of Mass. estimates[12] for use of ammonia was based on heat exchanger ratios from Ref. 15 and turbine ratios from Ref. 27.

Table 3 Estimated power costs at shore for Gulf Stream plants[a]

	Working fluid					
	Propane			Ammonia		
Capital costs, $\$/kw_e$:						
Basic OTEC plant	629			465		
Power conversion/transmission system to shore	83			83		
Subtotal	712			548		
Add 12% for interest and escalation during construction	85			66		
Total capital cost, $\$/kw_e$	797			614		
Fixed charge rate, %	15	13	7	15	13	7
Costs in mills/kw_ehr:						
Fixed charge at 0.9 load factor	15	13	8	12	10	5.4
Operating cost	1	1	1	1	1	1
Power at shore	16	14	8	13	11	6.4

[a] Based on "high" capital costs from Ref. 12 and 32°F ΔT.

form as well as the heat exchangers and can foresee getting the plant cost down to $\$1100/kw_e$.[20]

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 CMU 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 hereinafter) will have the lowest effective power-plant capital costs and busbar power costs. With these comments in mind, Tables 3-5, based on estimates from Table 2 (as in the original AIAA Paper 75-617) 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 seems probable that it will affect the competitive system in Table 1 (via fuel costs) even more than OTEC plants; e.g., the OPEC countries are already talking of further increases in crude oil prices.

Table 3 shows the U. Mass. estimates for total capital cost of getting the power to shore, including effects of interest and esclation during construction. These capital costs are well below the "allowable" range in Table 1. They have been converted to power costs for three assumed fixed-charge rates, 15%, 13%, and 7%, the last being typical of public utility financing. The resulting estimated power cost range of 6 to 16 mills/kwh is indeed attractive. If the capital cost for the plant using ammonia tripled, to $\$1842/kw_e$, and public utility financing yielding 7% fixed charges were arranged, the cost still would be 16 mills/kwh.

Production of Ammonia at a Tropical OTEC Plant

Production of ammonia at a floating, tropical OTEC plant is attractive because:

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%-6% per year. The result is a projected shortfall of 40 trillion ft³. The domestic ammonia picture is correspondingly bleak. If existing plants continue to receive as much gas as they do today, the projected ammonia short-fall by 1985 is 10 million tons (Fig. 13).[38] 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 sea water and nitrogen from the air.

The ammonia production concept is illustrated in Figs. 14 and 15. 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 sea-water 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

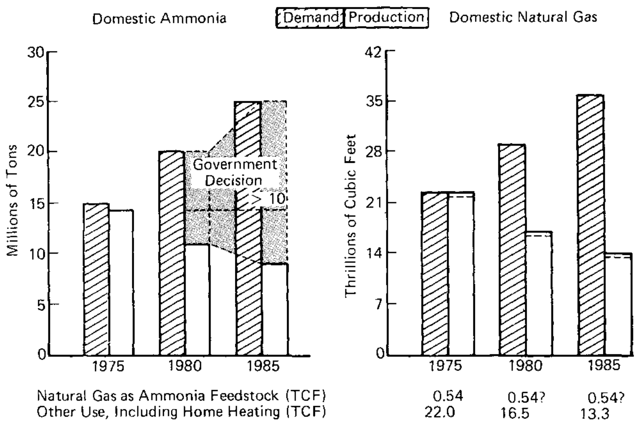

Fig. 13 Forecasts of U.S. demand and production for ammonia, assuming it continues to be made from natural gas, whose supply diminishes by 35% by 1985.

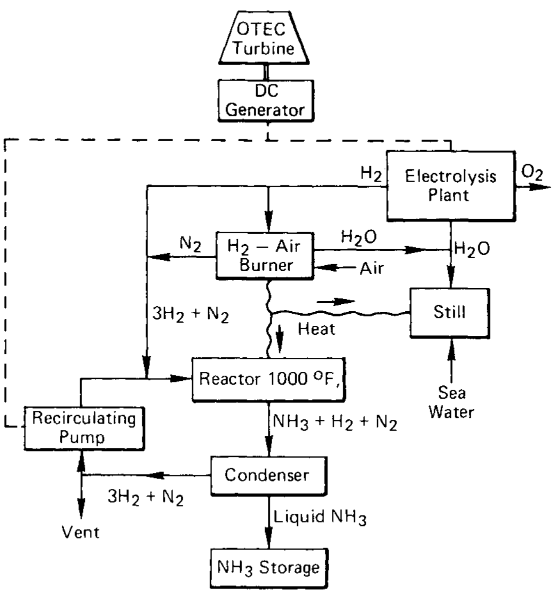

Fig. 14 Schematic arrangement for an OTEC-NH_3 plant.

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 $1N_2$ to $3H_2$ 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 more costly and maintenance-demanding oil- or coal-reforming portions of those plants. Further use of the oxygen produced by the electrolysis 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.

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-\$72/ton (1974 dollars), compared to recent *price*

Table 4 Estimated costs for producing ammonia at a tropical OTEC plant with 39°F ΔT^a

Plant cost to busbars (Table 2), \$/kw$_e$	\$357	
Add ammonia plant (Fig. 15)	90	
Total plant investment, \$/kw$_e$	\$447	
Basis: 500 Mw$_e$ plant producing 475,000 ton/yr at 0.9 load factor		
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[a,b]	Conventional	ExIm Bank[b]
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 ports, \$/ton	72	63

[a] Based on type of ammonia production costing used in Ref. 39. Maintenance is lower than in Ref. 39, because only a portion, which requires least maintenance, of a natural-gas-fed ammonia plant is needed here.

[b] 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, funded an ammonia plant.[37]

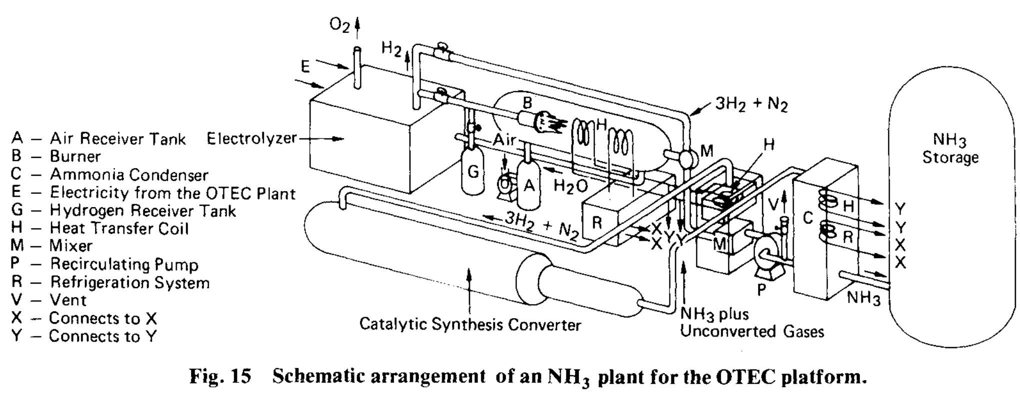

Fig. 15 Schematic arrangement of an NH_3 plant for the OTEC platform.

quotations of \$145-\$165/ton at the plant gate or \$215-\$245/ton delivered.

The interfacing problems for liquid ammonia would simply relate to expansion of shipping and port handling capabilities. At a "plant gate" price of \$165/ton, the value of the ammonia produced by one 500-Mw_e plant (475,000 tons/yr or 3% of current U.S. production) in 3 to 4 years would be equal to the capital investment in the plant.

Other Potential Products from Tropical OTEC Plants

The electrolytic reduction of alumina (made from bauxite on shore) to aluminum on OTEC plants is an attractive candidate because it is an electric-power-intensive process, and part of the market 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 Zener's estimates for exchangers using small fluted tubes[15]; the high value, for use of plain, 9-in.-diam tubes for plants in the tropics.) That is a large amount of aluminum, but one tropical OTEC plant could produce enough to make 2 to 6 more plants (including portions of platform structures) of the same size every year.

Use of aluminum in automotive vehicles and trains can be expected to increase as efforts continue to reduce weight of all rolling stock in order to reduce fuel requirements. And it 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). 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 be equal to the plant investment cost in about 3 years.

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 GH_2 produced there to make synthetic oil, methane, or methanol. Gregory and Biederman[18m] are studying some of these possibilities.

For the longer term, the production of liquid hydrogen (LH_2) fuel for shipment to U.S. and foreign ports is expected to be attractive. The estimates shown in Table 5 suggest a delivered cost of \$4-5/10^6 Btu, which is below the present cost (approximately \$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 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 also should be evaluated.

When LH_2 is delivered by tankers from OTEC plants, facilities at deep-water ports will be needed to transfer to match the requirements of a domestic, gaseous hydrogen (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 aricraft 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.

Table 5 Cost estimates for producing liquid hydrogen (LH_2) at a tropical OTEC plant and shipping 3000 miles to ports

Plant costs, \$/kw_e:		
Basic OTEC plant	357	
High-pressure 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[b]	0.56	0.56
Shipping cost	0.50	0.50
Cost at port, \$/10^6 Btu	4.84	3.97
Equivalent gasoline cost, \$/gal[c]	0.56	0.45

[a]Basis: Electrolysis plant operates at 85% efficiency to produce GH_2 at 3000 psia; liquefaction plant, at 80% efficiency; 1.47 kw_e hr from plant are needed for each kw_t hr of LH_2 produced.
[b]Equivalent to 1.3 mills/kw_e hr of power required.
[c]Not including taxes, storage and distribution costs, and profit on shore; energy content of gasoline, 115,000 Btu/gal.

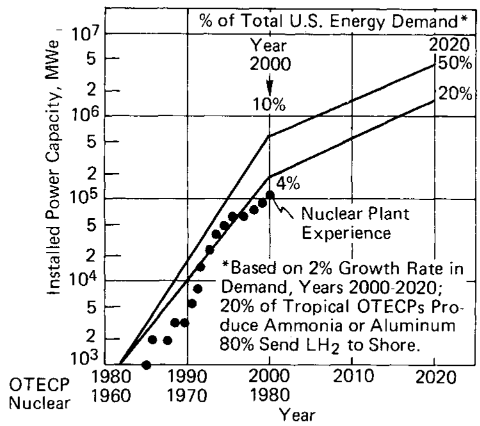

Fig. 16 Potential expansion rate and U.S. market capture for Ocean Thermal Energy Conversion Power Plants. (Reference data for nuclear plants from Ref. 36.)

Potential Growth Rate for Tropical OTEC Plants

The current U.S. energy requirement is approximately 80×10^{15} Btu/yr or 80 Q, and most projections anticipate that it will at least double, to 160 Q, by the year 2000. Tropical OTEC plants ultimately could provide many times the U.S. energy requirement.

Many participants at the 3rd OTEC Workshop[18] 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: a) The ability to obtain the needed raw materials (e.g., bauxite for making aluminum)‡ and/or metals for making heat exchangers (mostly aluminum), turbines (aluminum and/or steel), generators (steel and copper), and platforms (aluminum, steel, and concrete). b) The ability to provide the manpower and construction facilities required to build the platforms (in shipbuilding facilities) and components (but no appreciable requirements for expansion is expected until the rate exceeds the order of 6-10 plants/yr of 500-Mw_e size). c) The ability to provide trained, seagoing engineering/construction crews and towing tender ships to accomplish the overall plant erection and startup process at sea. d) 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. 36, the achievement of 200 Gw_e capacity by the year 2000 would correspond well with the expansion rate (lower curve slope in Fig. 16) 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. 16 seems reasonable.

Data and Technology Needs

No technological breakthroughs are required to produce OTEC plants that can produce electric power or suitable products at competitive costs. However, economic, scientific, and engineering data will be needed in the following areas to establish the role of such plants in the future U.S. economy.

a) *Economics*. The analyses of integrated-system, lifetime economics needed by the government and investors, and realistic comparisons with costs of alternative power or manufacturing plant systems, must be made and successively improved as performance data and production techniques are developed from pilot/demonstration plant work.

b) *Oceanographic and atmospheric data*. More detailed data are needed for candidate sites, particularly in tropic oceans where temperature differences of 20-23°C exist.

c) *Environmental effects data*. Experiments on the downstream effects of the discharged undersea plumes from the evaporators and condensers, conducted in part during pilot and/or demonstration plant operations, are needed to verify calculations of environmental impacts and establish siting limitations for spacing of plants within particularly desirable ocean areas. The potential positive value of upwelling as a source of nutrients for mariculture must be established in the context of an OTEC plant site. Effects of leaching of materials or spills of the working fluid from the OTEC plant, and recovery times from specific events, must be analyzed and supported by appropriate experiments at sea.

‡Note again that no raw materials other than sea water 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.

d) *Heat exchangers*. Experimental data on selected heat exchanger designs are urgently needed to verify the theoretical predictions. Effects of scale and corrosion in the sea water environment on heat exchanger performance as a function of time must be determined from pilot/demonstration plant work. The relationship between sea-water velocity and marine biofouling rate in the evaporator in selected designs at candidate sites must be established as soon as possible, and the present assessment that biofouling will not be a problem in the condensers must be validated. If biofouling can not be avoided by keeping water velocity above 5-8 fps, techniques and costs for avoiding it by chlorination or other antifouling measures, and/or removing it by periodic cleaning, must be developed.

e) *Turbines, generators, and pumps*. Existing design and cost data from industry on machinery meeting or bracketing the needs for OTEC plants must be correlated to provide the basis for specifications for initial units for demonstration plants as well as for inputs to system optimization studies. At each stage of development (pilot plant, demonstration plant, first full-scale unit) data on efficiencies, wear, corrosion, shaft seal capabilities, etc. must be collected and analyzed.

f) *Cold water pipe and platform*. Existing design, assembly, and cost information on stable ocean platforms, offshore oil drilling rigs and other marine structures that incorporate features of interest for OTEC plants should be collected and correlated to assure that the plant design principles employed are reasonable and consistent with established marine experience. However, care must be taken to avoid unnecessary and costly overdesign for the mild environment of the doldrum tropical regions.

Suggested Implementation Plan

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 items.

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

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 210-640 Gw_e total capacity (4% to 10% of U.S. total energy demand) in operation by the year 2000.¶

Conclusions

The engineering feasibility for ocean thermal energy conversion (OTEC) plants, with emphasis shifted from Claude's open-cycle process of 1930 to the closed-Rankine-cycle process, 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.

¶Based on meeting all U.S. ammonia needs, with 5%/yr increase in demand for ammonia, 1985-2000 (25×10^6 ton/yr in 1985), and all U.S. Aluminum needs, with 3%/yr increase in demand, 1975-2000, and using the rest 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).

Becauuse of 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.

References

[1]Claude, G., "Power from Tropical Seas," *Mechanical Engineering*, Vol. 52, Dec. 1930, pp. 1039-1044.

[2]Walters, S., "Power in the Year 2001—Part 2—Thermal Sea Power," *Mechanical Engineering*, Vol. 93, Oct. 1971, pp. 21-25.

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

[4]Anderson, J. H. and Anderson, J. H., Jr., "Power from the Sun by Way of the Sea," *Power*, Jan.-Feb. 1965, pp. 64-65.

[5]Anderson, J. H. and Anderson, J. H., Jr., "Thermal Power from Sea Water," *Mechanical Engineering*, April 1966, pp. 41-46.

[6]Anderson, J. H., Jr., "Economic Power and Water from Solar Energy," Paper 72-WA/Sol-2, ASME Winter Annual Meeting, Nov. 1972.

[7]Lavi, A., ed., "Solar Sea Power Plant Conference and Workshop," NSF Grant No. GI-39115, June 27-28, 1973, Carnegie-Mellon Univ., Pittsburgh, Pa.:

a) Anderson, J. Hilbert, "Turbines for Sea Solar Power Plants," pp. 126-152.

b) Heronemus, W. E. and McGowan, J. G., "Some Views on Solar Sea Power Plants, A Project Sponsored by NSF-RANN," pp. 21-59.

c) Zener, C. and Lavi, A., "Drainage Systems for Condensation," pp. 60-95.

d) Olsen, H. L., Dugger, G. L., Shippen, W. B., and Avery, W. H., "Preliminary Considerations for the Selection of a Working Medium for the Solar Sear Power Plant," pp. 185-204.

e) Barnea, J., "Multiple Uses of the Claude Process," pp. 177-184.

[8]Heronemus, W. E., et al., "Annual Progress Report Covering the Period 1 January 1973 to 31 December 1973, Energy Program," Report NSF/RANN/SE/GI-34979/PR/73/3, Jan. 1974, University of Massachusetts, Amherst, Mass.

[9]McGowan, J. G., et al., "Conceptual Design of a Rankine Cycle Powered by the Ocean Thermal Difference," presented at 8th Intersociety Energy Conversion Engineering Conference (AIAA, ACS, AIChE, ANS, ASME, IEEE, SAE), Philadelphia, Pa., Aug. 1973.

[10]Heronemus, W. E., et al., "Technical and Economic Feasibility of the Ocean Thermal Differences Process as a Solar-Driven Energy Process," Semi-Annual Progress Report, Rept. NSF/RANN/SE/GI-34979/PR/74/2, University of Massachusetts, Amherst, Mass., July 1974.

[11]McGowan, J. G. and Connell, J. W., "Heat Exchanger Design for Ocean Thermal Difference Power Plants," ASME Paper 74-WA/OcT-4, ASME Winter Annual Meeting, New York, Nov. 1974.

[12]McGowan, J. E. and Heronemus, W. E., "Gulf Stream Based Ocean Thermal Power Plants," AIAA Paper 75-643, Los Angeles, Calif., 1975.

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

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

[15]Zener, C., et al., "Solar Sea Power, Third Quarterly Progress Report," Carnegie-Mellon Univ., Pittsburgh, Pa., Report NSF/RANN/SE/GI-39114/PR/74/3, April 1974.

[16]Zener, C., "Size Limitations on Solar Sea Powerplants," AIAA Paper 75-618, Los Angeles, Calif., 1975.

[17]Harrenstein, H. H., ed., *Second Ocean Thermal Energy Conversion Workshop*, conducted by the Clean Energy Research Institute, University of Miami, for the National Science Foundation (RANN), at Washington, D. C., Sept. 1974.

[18]Dugger, G. L., ed., *Proceedings, Third Workshop on Ocean Thermal Energy Conversion (OTEC), Houston, Texas, May 8-10, 1975*, SR 75-2, Aug. 1975, Applied Physics Laboratory, The Johns Hopkins University, Laurel, Md.

a) Trimble, L. C., Messinger, B. L., and Ulbrich, H. G., "OTEC System Study Report," Lockheed Missiles and Space Co., Sunnyvale, Calif.; Smith, Geoffrey, Bechtel Corp., San Francisco, Calif.; and Lin, T. Y., T. Y. Lin International, San Francisco, Calif.

b) Douglass, Robert H., "Ocean Thermal Energy Conversion: An Engineering Evaluation," Ocean and Energy Systems, TRW, Inc., Redondo Beach, Calif.

c) Goss, W. P., Heronemus, W. E., Mangarella, P. A., and McGowan, J. G., "Summary of University of Massachusetts Research on Gulf Stream Based Ocean Thermal Power Plants," University of Massachusetts, Amherst, Mass.

d) Lavi, A., "Solar Sea Power Plants, Cost and Economics," Carnegie-Mellon University, Pittsburgh, Pa.

The next 21 papers (e-y) are on new programs:

e) Barr, R. A., "Evaluation of Platform Designs for Ocean Thermal Power Plants," Hydronautics, Inc., Laurel, Md.

f) Bretschneider, C. W., "Operational Sea State and Design Wave Criteria, A Generalized Study for OTEC," University of Hawaii, Honolulu, Hawaii.

g) Anderson, J. H. and Anderson, J. H., Jr., "Cold Water Pipe: A Design Feasibility Study," Sea Solar Power, Inc., York, Pa.

h) Little, T. E., "Deep Water Pipe and Mooring Study Proposal," Westinghouse Electric Corp., Annapolis, Md.

i) Valent, P. J. and Taylor, R. J., "Anchor Systems for Ocean Thermal Energy Conversion Power Plants," Civil Engineering Lab., Naval Construction Battalion Center, Port Hueneme, Calif.

j) Haynes, H. H., "Feasibility of Submerged Concrete Structures," for OTEC Power Plants, Civil Engineering Lab., Naval Construction Battalion Center, Port Hueneme, Calif.

k) Chen, W. F., "Reinforced Concrete Constitutive Relations, for Application to OTEC Plant Structures," Lehigh University, Bethlehem, Pa.

l) Winer, B. M., "Electrical Energy Transmission from Ocean Thermal Power Plants," Arthur D. Little, Inc., Cambridge, Mass.

m) Gregory, D. P. and Biederman, N. P., "An Optimization Study of Ocean Thermal-Energy Delivery Systems Based on Chemical-Energy Carriers," Institute of Gas Technology, Chicago, Ill.

n) Hornburg, C. D., Lindal, B. and El-Ramly, N., "Preliminary Research on an Ocean Energy Industrial Complex," DSS Engineers, Inc., Ft. Lauderdale, Fla.

o) Roels, O. A., "The Economic Contribution of 'Artificial Upwelling' Mariculture to Sea-Thermal Power Generation," Lamont-Doherty Geological Observatory of Columbia University, Palisades, N.Y.

p) Sabin, C. M., Poppendiek, H.F., and Sellers, A.J., "Nucleating Vaporization and Extended Surface Heat Transfer at Temperature Difference," Geoscience Ltd., Solana Beach, Calif.

q) Rothfus, R. R., "Concurrent Studies of Enhanced Heat Transfer and Materials for Ocean Thermal Exchangers," Carnegie-Mellon University, Pittsburgh, Pa.

r) Iqbal, K. Z. and Starling, K. E., "Potential Advantages of Mixtures as Working Fluids in the OTEC Cycles," The University of Oklahoma, Normàn, Okla.

s) Jones, P. E. and Ostrozynski, R. L., "The Prevention of Biofouling of Heat Transfer Surfaces of Ocean Thermal Energy Converters," Allied Chemical Corp., Buffalo, N.Y.

t) Fetkovich, J. G., Bernstein, I. M., Granneman, G., "A Study of Fouling and Corrosion Problems in a Solar Sea Power Plant," Carnegie-Mellon University, Pittsburgh, Pa., and Munchmeyer, F.C., University of Hawaii, Honolulu, Hi.

u) Atwood, D. K., "A Case Study of Resource Assessment and Environment Impact Using a Proposed Puerto Rico Site," University of Puerto Rico, Mayaguez, Puerto Rico.

v) Wolff, P. M., "OTEC Plan for Resource and Environmental Studies," Ocean Data Systems, Inc., Monterey, Calif.

w) Piacsek, S. A., Toomre, J., Roberts, G. and Warn-Varnas, A., "Thermocline Perturbations and Available Temperature Contrast for Ocean Thermal Power Plants," Naval Research Lab., Washington, D. C.

x) Knight, H. G., Nyhart, J. D., and Stein, R. E., "Legal Considerations of OTEC: Some Initial Views," American Society of International Law, Washington, D. C.

y) Dugger, G. L., et al., "Tropical Ocean Thermal Power Plants Producing Ammonia or Other Products," APL/JHU, Laurel, Md.

z) Cohen, R., "OTEC Program Overview," Solar Energy Div., Energy Research and Development Administration, Washington, D.C.

The next 5 papers (aa-ee) are on continuing or completed programs:

aa) Czikk, A. M., Fenner, G. W., Notaro, F., and Zawierucha, R. "OTEC Heat Exchangers," Linde Div., Union Carbide Corp., Tonawanda, N.Y.

bb) Surratt, W. B., Hart, G. K. and Sieder, E. M., "Plastic Heat Exchangers for Ocean Thermal Energy Conversion," DSS Engineers, Inc., Ft. Lauderdale, Fla.

cc) Bathen, K. T., "Oceanographic and Socio-Economic Aspects of an OTEC Proof-of-Concept Test Site in Hawaii," University of Hawaii at Manoa, Honolulu, Hawaii.

dd) Hanson, J. A., "Scale Model Studies of OTEC Platform and Cold Water Pipe Hydrodynamics," the Oceanic Foundation, Makapuu Point, Waimanalo, Hawaii.

The final three papers are on company-supported programs:

ee) Dexter, S. C., "Control of Microbial Slime Films," Woods Hole Oceanographic Institution, Woods Hole, Mass.

ff) Brown, C. E. and Wechsler, L., "Engineering an Open Cycle Power Plant for Extracting Solar Energy from the Sea," Hydronautics, Inc., Laurel, Md.

gg) Rabenhorst, D., "Superflywheels for Storing Energy from OTEC Plants," Applied Physics Lab., The Johns Hopkins University, Laurel, Md.

hh) Mayo, K.E., "The Tuned Sphere Stable Platform—A Candidate for OTEC Plants," Tuned Sphere International, Nashua, N.H.

[19] Trimble, L. C. and Messigner, B., "Ocean Thermal Energy Conversion System Evaluations," AIAA Paper 75-616, Los Angeles, Calif., 1975.

[20] Douglas, R. H., "Systems Aspects of Ocean Thermal Energy Conversion," AIAA Paper 75-615, Los Angeles, Calif., 1975.

[21] Killian, H. J., Dugger, G. L., and Grey, J., eds., *Solar Energy for Earth, An AIAA Assessment*, April 1975, AIAA, New York, N.Y.

[22] Dugger, G. L., "Power from the Ocean Thermal Gradient," *Astronautics & Aeronautics*, to be published.

[23] *1975 Offshore Technology Conference, May 1975, Houston, Texas, Proceedings, Vol. II*, Offshore Technology Conference Office, Dallas, Texas:

a) Douglas, R. H. Jr., Hollett, J. S. and Karalis, A. J., "Ocean Thermal Energy: An Engineering Evaluation," Paper OTC 2252, pp. 87-100.

b) Trimble, L. C. and Naef, E. P., "Ocean Thermal Energy Conversion," Paper OTC 2258, pp. 155-166.

[24] Fuglister, F. C., *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.

[25] Veziroglu, T. N., ed., *The Hydrogen Economy Miami Energy (THEME) Conference*, March 1974, Miami Beach, Fla.

[26] Griffin, O. M., "The Ocean as a Renewable Source of Energy," ASME Paper 74-WA/OcT-5, ASME Winter Annual Meeting, New York, Nov. 1974.

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

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

[29] Crosby, R. M., "Ocean Instrumentation: The Better Use of Materials Technology," 1970 IEEE International Conference on Energy in the Ocean Environment," Panama City, Fla., Sept. 1970.

[30] Webb, L. D., "Uses of Materials in Offshore Structures," *Oceanology International*, March 1970, p. 19.

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

[32] Verink, E. D., Jr., "Aluminum Alloys for Saline Waters," *Chemical Engineering*, Vol. 81, April 15, 1974, pp. 104-110.

[33] Milton, R. M. and Gottzman, C. F., "High Efficiency Reboilers and Condensers," *Chemical Engineering Progress*, Vol. 9, Sept. 1972, pp. 56-61.

[34] 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, April 18, 1975.

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

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

[37] "Export-Import Bank Program Review," Senate Rept. S241-6, Feb. 1974, Washington, D.C.

[38] Anon., "International Trade in Ammonia May Rise Sharply," *Chemical & Engineering News*, Vol. 52, Aug. 5, 1974, pp. 13-14.

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