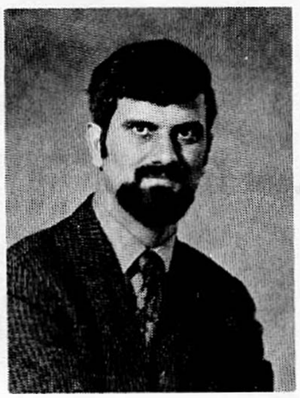
IEEE COUNCIL ON OCEANIC ENGINEERING NEWSLETTER

EDITOR: HAROLD A. SABBAGH **ISSUE NO. 16—MARCH 1979**



EDITOR'S COMMENTS

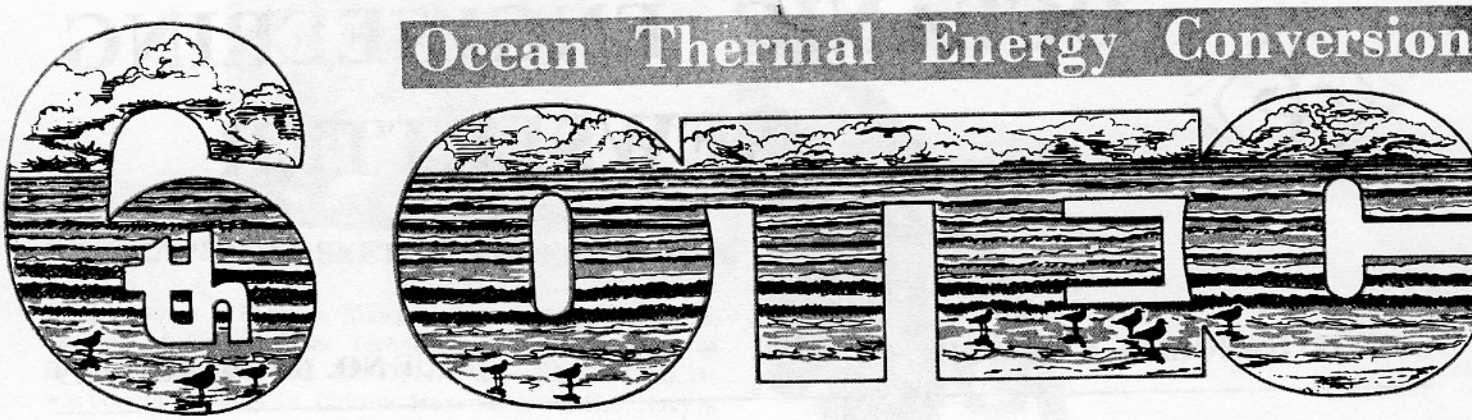
In hurrying to get the December issue's manuscript to IEEE Headquarters in early November, I completely forgot that that issue was the year-end issue and marked the completion of my first year as editor of this Newsletter. What's bad is that I forgot to thank the Council members for their assistance and encouragement; what's worse is that I forgot to wish you readers a Merry Christmas and a Happy New Year. Imagine the problem that I'll be facing this year, however, when material for the Newsletter must be in to Headquarters *two* months before the issue mailing date. That means that I'll be sending in the year-end issue's manuscript in the middle of October—before Halloween, even. Now there's no way that I'm going to remember to wish you a Merry Christmas and a Happy New Year before Halloween, so I'd better do it now, while it's still fresh in my mind: Merry Christmas and a Happy New Year.

As you recall, in the September issue I sought your advice on matters pertaining to the Newsletter. Mr. H. E. Dempsey, with Dollman Electronics Canada Ltd., promptly responded by requesting articles on digital communications in underwater channels. I discussed the matter with Don Bolle, Editor of the Journal, who liked the idea so much that he wants to publish some papers on the subject in the Journal. So keep those cards and letters coming; we'll try to be responsive.

Our feature article is "An Overview of the U.S. OTEC Development Program" by Dr. Robert Cohen, U.S. Department of Energy. This paper was an invited presentation at the ASME 1978 Energy Technology Conference, Houston, Texas, November 6–9. It appears, also, in a publication of the ASME Ocean Energy Division (OED-Vol. 5). Readers interested in knowing more about oceanic energy conversion should consult that book. We thank Dr. Cohen and the ASME for permission to publish the article, and Joe Vadus for recommending Dr. Cohen.

Harold A. Sabbagh
Code 7055
Naval Weapons Support Center
Crane, IN 47522

Announcement & Call for Papers



CONFERENCE

"Ocean Thermal Energy for the 80's"

WASHINGTON, D. C. June 19–22, 1979

Shoreham – Americana Hotel

Sponsored by
Ocean Systems Branch
Division of Central Solar Technology
U.S. Department of Energy

Organized by
Applied Physics Laboratory
The Johns Hopkins University

NEWSLETTER EDITOR

Harold A. Sabbagh
Naval Weapons Support Ctr.
Code 7055
Crane, IN 47522
(812) 854-1363

IEEE Council on Oceanic Engineering Newsletter is published quarterly by the Council on Oceanic Engineering of the Institute of Electrical and Electronics Engineers, Inc. Headquarters: 345 East 47 Street, New York, NY 10017. Sent automatically and without additional cost to each member of the Council on Oceanic Engineering. Printed in U.S.A. Second-class postage paid at New York, NY and at additional mailing offices.

AN OVERVIEW OF THE U.S. OTEC DEVELOPMENT PROGRAM

BY Robert Cohen

Oceans Systems Branch
Division of Central Solar Technology
U. S. Department of Energy
Washington, D.C. 20545

Ocean Thermal Energy Conversion (OTEC) is one of the solar energy options for which technology is being developed by the U.S. Department of Energy. Successful demonstration of OTEC systems may be achieved by 1985, followed by construction of commercial OTEC power plants up to about 500 MWe net power output. These plants will produce electricity for transmission to shore by submarine cable and for the manufacture of energy-intensive products such as ammonia, hydrogen, and aluminum. In the past year, significant test results have been obtained regarding thermal performance of OTEC heat exchangers and on biofouling, cleaning and corrosion of the exchangers. Major system studies are being conducted on the power subsystems, platform, cold water pipe, and submarine cables. Test results and conclusions from the subsystem studies are presented, including cost projections and OTEC economics and market penetration analyses.

INTRODUCTION

This paper describes the status of engineering development and future commercial prospects of Ocean Thermal Energy Conversion (OTEC). The description is from the standpoint of the U.S. OTEC development program. That program is oriented toward catalyzing the introduction of OTEC technology that will provide a substantial amount of electrical energy both as an end-use and for the manufacture of energy-intensive products. The paper summarizes the program for development and testing of system hardware, with emphasis on heat-exchangers. Introduction of this technology requires the achievement of viable system costs so as to penetrate competitive markets. Such market penetration will require prior resolution of legal, institutional and financial problems associated with the introduction of this new technology. Those aspects, along with potential market penetrations, will be considered, since they are an essential adjunct of the development program.

Although OTEC technology is presently being developed by the Japanese Government(1), the French Government, and EUROCEAN (2) as well as by the United States Government (3), (4), the Japanese and European programs are rather modest compared to the United States OTEC development program. Accordingly, the discussion in this paper is limited to a description of the United States program.

[1] The views expressed herein are those of the author, and are not necessarily, in all or in part, those of the U.S. Department of Energy. Much of this material was excerpted from a chapter on OTEC to appear in Solar Energy Handbook (Marcel Dekker, Inc., New York, 1979).

Federal support of OTEC development began in 1972, as part of the United States solar energy program. The evolution of funding is shown in the following table:

Fiscal Year:	1972	1973	1974	1975	1976[2]	1977	1978
Amount of budgetary authority:	$0.1	0.2	0.7	3.0	8.6[2]	14.5	36.0M

A total of about $300,000 of these sums was expended during FY 1977 and 1978 for research on technology for the utilization of other renewable ocean energy resources (waves, currents, and salinity gradients).

In recent years, the United States OTEC program has moved rapidly from paper and laboratory studies into testing of hardware at significant sizes in both land and sea environments. Note that funding in each fiscal year somewhat exceeds the cumulative funding for the preceding fiscal years, with the result that the total available information and the complexion of the program are changing rapidly. The United States OTEC program began at the National Science Foundation (NSF), and was subsequently transferred to the Energy Research and Development Administration (ERDA) on January 19, 1975. ERDA became part of the U.S. Department of Energy (DOE) on October 1, 1977.

The DOE OTEC technology development program is aimed at developing and testing viable OTEC components, subsystems and complete systems. Activities in that program are divided into three complementary facets, as shown in Figure 1, to provide candidate test hardware for closed cycle ammonia systems.

Three Phase Development Program

Small Scale 1MWt	Large Ocean Test 1MWe (40MWt)	Pilot Plant ≥ 5MWe
Biofouling – Single Tube Cleaning – Single Tube Corrosion – Test Sample Thermal Performance – Single Tube + Core Test	Multiple Large Scale Heat Exchanger Tests • Configuration (5) • Material (3) • Working Fluid • Enhancements (3) • Biofouling Control (3) Cold Water Pipe (6′ Dia.) • Loads • Deployment	Power Plant Test Cold Water Pipe Electric

Figure 1. Three Complementary Facets of the U.S. National OTEC Development Program

POWER CYCLES

Two basic power cycles have been advocated for conversion of ocean thermal energy: the so-called "open cycle", employing seawater as the working fluid, and the so-called "closed cycle", utilizing other working fluids (such as ammonia, hydrocarbons, or halocarbons). The first published work on OTEC by d'Arsonval in 1881 (5), suggested a closed cycle, and that article proposed sulfur dioxide as the working fluid. However, the first OTEC experiments by Claude in the 1920's (6) utilized an open cycle, where seawater was evaporated under a partial vacuum.

[2] Includes an additional 3 months and the associated funding.

Open and Hybrid Cycles

Although key emphasis is being placed on developing hardware for closed cycle ammonia systems, system studies of the open and hybrid cycles are being conducted. Also, the program is supporting analytical and laboratory studies of "foam" and "mist" approaches to the open cycle. Insofar as results warrant, hardware development emphasis could be shifted from the closed cycle to the open cycle for second-generation systems.

The "open cycle" refers to the utilization of seawater as the working fluid, wherein seawater is flash evaporated under a partial vacuum. The low pressure steam is passed through a turbine, which extracts energy from it, and thence the spent vapor is cooled in a condenser. This cycle derives the name "open" from the fact that the condensate need not be returned to the evaporator, as in the case of the "closed" cycle. Instead, the condensate can be utilized as desalinated water if a surface condenser is used, or–if a spray (direct contact) condenser is used–the condensate is mixed with the cooling water and the mixture is discharged back into the ocean. A schematic diagram of the open cycle system is shown in Figure 2. Since the early OTEC experiments performed by Claude (6) utilized an open cycle, the open cycle system is sometimes referred to as a "Claude Cycle"

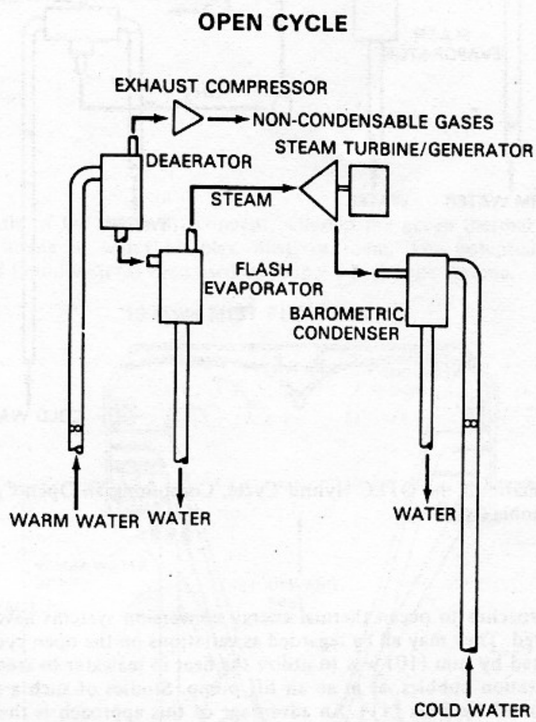


Figure 2. Schematic of the OTEC Open Cycle

Because of the need in the open cycle to harness the energy in low-pressure steam, extremely large turbines comparable to wind turbines must be utilized. Furthermore, degasifiers (deaerators) must be used to remove gases dissolved in the seawater unless one is willing to accept large losses in efficiency. On the other hand, since there are no heat transfer problems in the evaporator, the problem of biofouling control is minimized.

The cost of an open cycle system for producing substantial numbers of megawatts is presently regarded by most OTEC workers as being significantly greater than for a closed cycle system. An evaluation of costs for an open cycle system was recently completed by Watt, Mathews and Hathaway (7). The turbine cost constituted almost half the cost of the power system, but may be amenable to reductions that could result from design innovations.

There are several variations on the standard OTEC open cycle system. One variation is the "hybrid cycle", which is an attempt to combine the best features and avoid the worst features of the open and closed cycles. First, as shown in Figure 3, seawater is flash evaporated to steam, as in the open cycle. The heat in the resulting steam is then transferred to ammonia in an otherwise conventional closed Rankine cycle system. A comparative study of the closed (ammonia), open (steam), and hybrid cycles showed the closed cycle system to be most economical in cost and to require the least parasitic power (8).

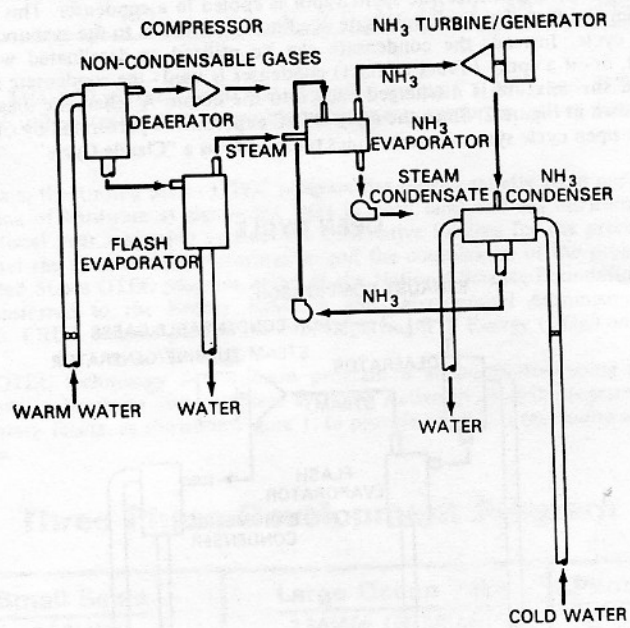


Figure 3. Schematic of the OTEC Hybrid Cycle, Combining an Open Cycle With a Closed Ammonia Cycle

Several other approaches to ocean thermal energy conversion systems have also been suggested and are being investigated. They may all be regarded as variations on the open cycle. An idea proposed by Beck (9) and patented by him (10) was to utilize the heat in seawater to create a column of water through producing cavitation bubbles, as in an air lift pump. Studies of such a steam lift pump have subsequently been reported by Beck (11). An advantage of this approach is that a hydraulic head is produced, thus allowing a hydraulic turbine to be used, rather than requiring a gas turbine. Zener and Fetkovich (12) suggested that the two-phase mixture of Beck have a foam structure. Ridgway (13) proposed that warm seawater be introduced as a mist that is then lifted against gravity by the flow of steam from a higher pressure region to a lower pressure region.

Figure 4 is a schematic diagram of these "lift cycle" approaches. They are analogous to the naturally-occurring hydrological cycle that leads to the production of solar hydropower. In the case of OTEC lift cycles, an artificial hydrological cycle is created within a large, ocean-going vessel. A 10 MWe version of a mist flow OTEC power plant concept by Ridgway (13) is shown in Figure 5. The bubble, foam and mist approaches thus convert a "temperature head" into a hydraulic head. They are advanced concepts that offer certain attractive features and are being investigated. However, they present a number of practical problems such as the potential stability and/or instability of the bubbles, foam, mist, and of the associated ocean platform. Some of these questions are discussed in an exchange between Henrie (14), Beck (15), and Zener and Fetkovich (16).

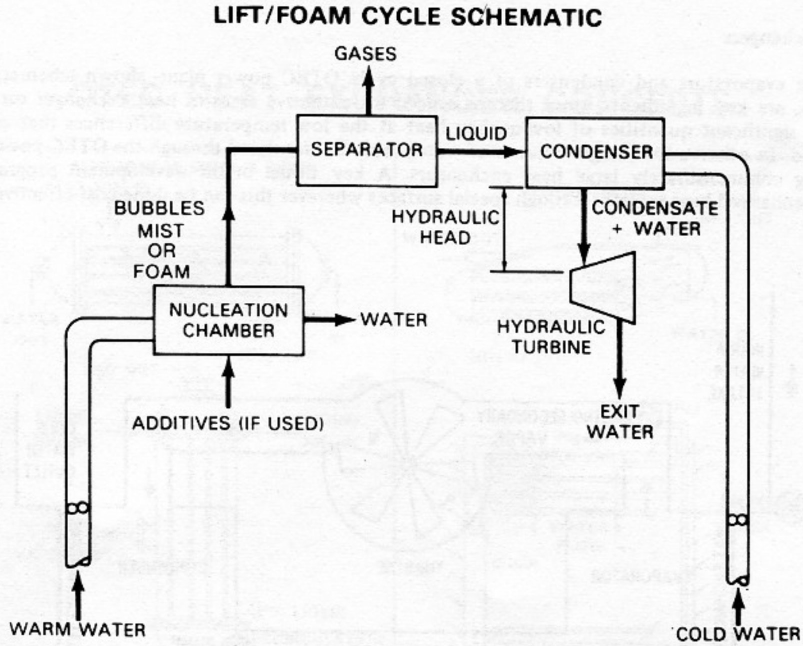


Figure 4. Schematic of the steam lift concept, wherein the ocean thermal gradient results in the lifting of water bubbles, mist, or foam. The potential energy of the elevated liquid water is then used to propel a hydraulic turbine.

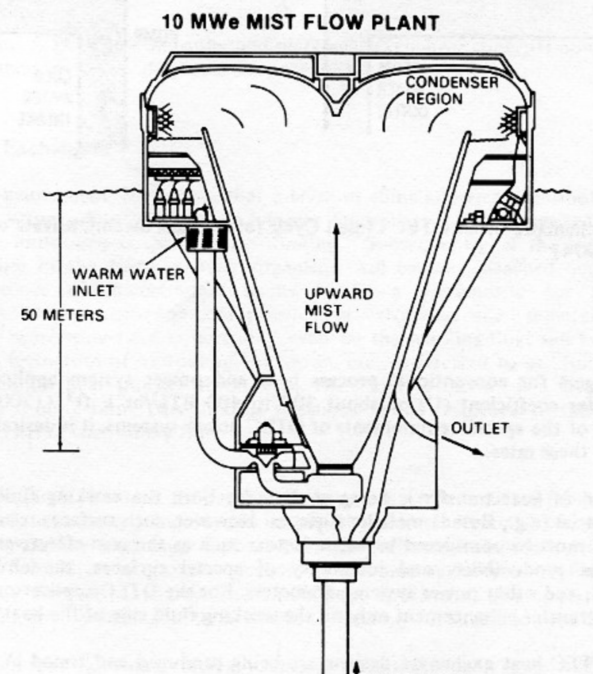


Figure 5. Schematic of a 10 MWe pilot plant that would utilize a mist flow concept proposed by Ridgway of R&D Associates. (Reference 13)

Closed Cycles

Heat Exchangers

The evaporators and condensers of a closed cycle OTEC power plant, shown schematically in Figure 6, are key ingredients, since there is a need for extensive areas of heat exchanger surfaces to transfer significant quantities of low-quality heat at the low temperature differences that are being exploited. In other words, large volumes of water must be circulated through the OTEC power plant, requiring commensurately large heat exchangers. A key thrust in the development program is to achieve enhanced heat transfer through special surfaces wherever this can be done cost-effectively.

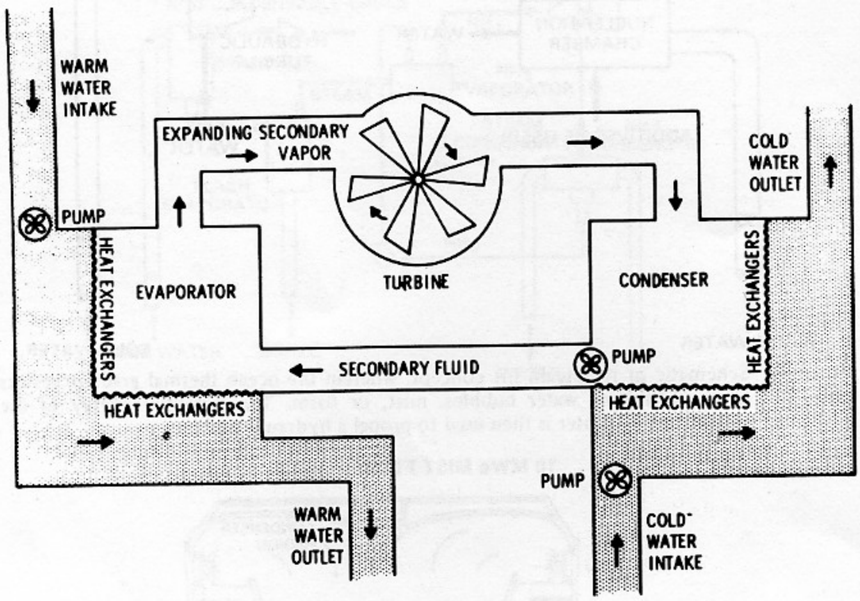


Figure 6. Schematic of an OTEC Closed Cycle (after Mark Swann, private communication, 1974)

Heat exchangers for conventional process heat and power system applications operate with overall heat transfer coefficient (U) of about 300 to 400 BTU/hr°F ft^2 (1700 to 2300 W/m^2 K). However, because of the special requirements of OTEC power systems, it is desirable to achieve values of U at least twice these rates.

Augmentation of heat transfer is being studied for both the working fluid sides and seawater sides, by using special (e.g., fluted) metallic surfaces. However, such surfaces result in additional cost, so that a tradeoff must be considered between factors such as the cost-effectiveness of heat transfer enhancements, the producibility and joinability of special surfaces, the ability to control the biofouling thereof, and other power system parameters. For the OTEC application, a likely possibility is to employ heat transfer enhancement only on the working fluid side of the heat exchangers.

Candidate OTEC heat exchanger designs are being produced and tested in laboratory and core test (1 MWt) units. Heat exchanger concepts under consideration fall into shell-and-tube categories and plate configurations. Sketches of some of these options are shown in Figure 7. Ammonia has been selected as the most likely working fluid, although the possibility of utilizing propane or a halocarbon is still being preserved. Testing is so far being conducted only with ammonia, however.

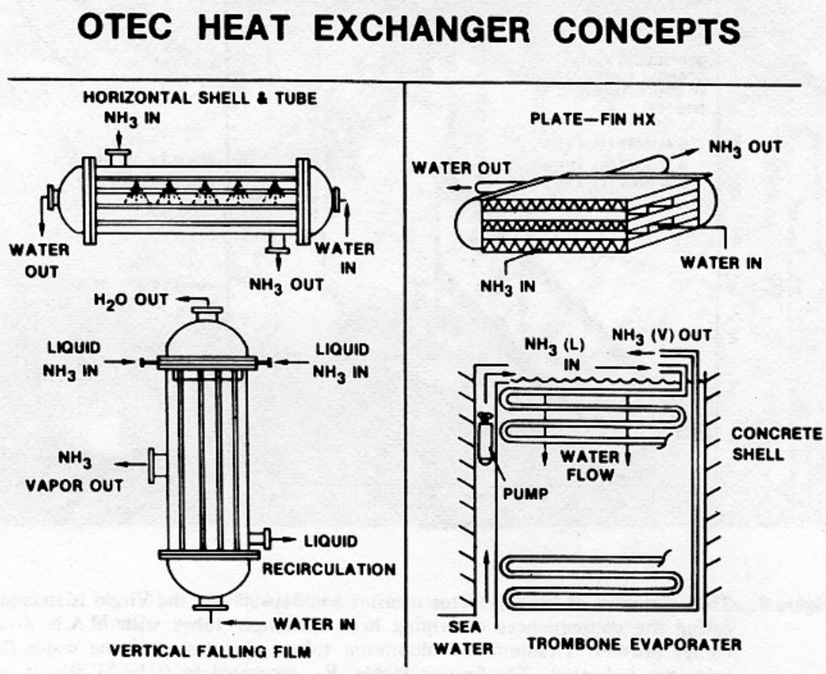


Figure 7. Some OTEC shell-and-tube and plate heat exchanger concepts now being studied in the U.S. OTEC development program.

Biofouling of Heat Exchangers

In an ocean environment, it is likely that a layer of slime known as "biofouling" will eventually accumulate on the water side of the heat exchangers. Such slime is first comprised of microorganisms, at which stage the biofouling is called "microfouling." Subsequently, if the slime is not removed, additional biofouling in the form of macroorganisms will become attached, augmenting the slime layer. The occurrence of microfouling seems to be a prerequisite for the attachment of macroorganisms. A film of corrosion and possibly of calcareous (i.e., mineral) deposits can also accumulate on the water-side (and conceivably even on the working-fluid side) of the heat transfer surfaces. The total formation of biofouling, corrosion, etc., is referred to as "fouling" (or "scaling") and will tend to inhibit heat transfer through it. The "fouling factor" is a measure of the thermal resistance, R_f, of a fouling film. This thermal resistance is the reciprocal of the corresponding heat transfer coefficient, h_f, of the fouling film.

To maintain viable OTEC heat exchangers, provision must be made to inhibit the formation of fouling layers and to remove any significant fouling that forms. Removal can be accomplished by periodically cleaning the heat exchanger surfaces through mechanical, chemical or other means. It is an important program objective to provide mechanical cleaning techniques to limit R_f to the range 0.0001 to 0.0003 hr.°F. ft^2/BTU (0.00002 to 0.00005 m^2 K/W), and cleaning tests conducted to date indicate that this objective is attainable by available technology for shell-and-tube heat exchangers.

It is anticipated that biofouling on heat exchangers located in open ocean waters will not develop as rapidly as at most coastal locations, where nutrients are more abundant. Measurements of the thermal resistance, R_f, of a biofouling layer forming on the seawater side of aluminum and titanium tubes located in water masses characteristic of the open ocean have been conducted in Hawaii and Saint Croix, V.I. The rates of accretion (cf. Figure 8) were such that the thermal resistance of the biofouling layer built up at the rate of about 0.0001 hr ft^2 °F/BTU (0.00002 m^2 K/W) per week, and preliminary results indicate that the layer was amenable to cleaning with a commercial brush produced by the M.A.N. (trade name) organization. The apparatus used to measure the thermal resistance of a biofouling layer was developed by John Fetkovich (17) of Carnegie-Mellon University.

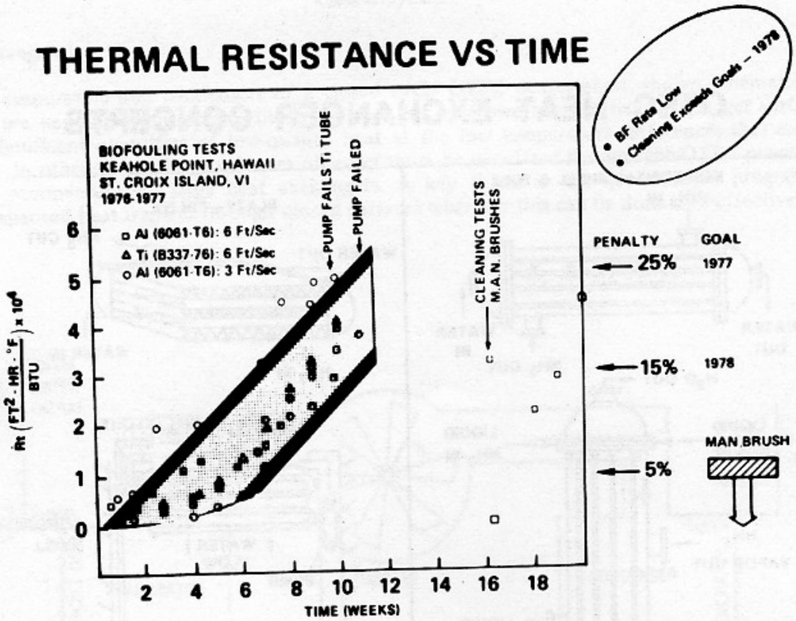


Figure 8. Time variation of fouling factor measured in Hawaii and the Virgin Islands indicating the consequences of wiping heat exchanger tubes with M.A.N. (trade name) brushes. Titanium and aluminum tubes were tested at the water flow velocities indicated. The fouling factor, R_f, measured in $ft^2 hr\ °F/Btu$ is converted to $m^2 K/W$ by multiplying by the factor 0.176. A given fouling factor is associated with a heat transfer penalty shown in percentages stated on the right-hand axis of ordinates.

Biofouling Countermeasures

Even though biofouling can be inhibited by the use of biocides such as chlorine (through continuous or intermittent dosing), provision for mechanical and/or chemical cleaning is regarded (from the standpoint of having a fail-safe method) as an important adjunct or substitute. Two mechanical devices presently in use to clean heat exchanger tubes are the M.A.N. brush and the Amertap (trade name) sponge-rubber ball. Other techniques include abrasive slurries and water jets. In order to test biofouling countermeasures and control systems under the accelerated rates of slime accretion available in coastal waters, the U.S. Department of Energy has established a heat exchanger cleaning test facility at the Naval Coastal Systems Laboratory, Panama City, Florida. A schematic drawing of that installation is shown in Figure 9.

Corrosion of Heat Exchangers

Although corrosion of OTEC heat exchangers would probably not be a problem if they were made of titanium, that metal is usually regarded as being a somewhat costlier alternative than use of some other candidate metals. In particular, aluminum is regarded as a strong candidate from the standpoint of cost, if it can be qualified technically. The key technical problem is the ability of a material to withstand erosion and corrosion in conjunction with mechanical cleaning methods in the presence of seawater and ammonia. Indications from previous experience are that aluminum surfaces maintained free of biofouling will not corrode as readily as those where biofouling is allowed to accumulate. Other metals (always an alloy, not the pure metal) under consideration include aluminum alloy 5052 (containing 2.5 percent magnesium), stainless steel (AL-6X), and copper alloy 706 (10 percent nickel). With ammonia as a working fluid, there is some concern as to whether the resulting corrosion rate of copper-nickel would be tolerable (18). Plastics have also been mentioned as a possible candidate heat exchanger material (19).

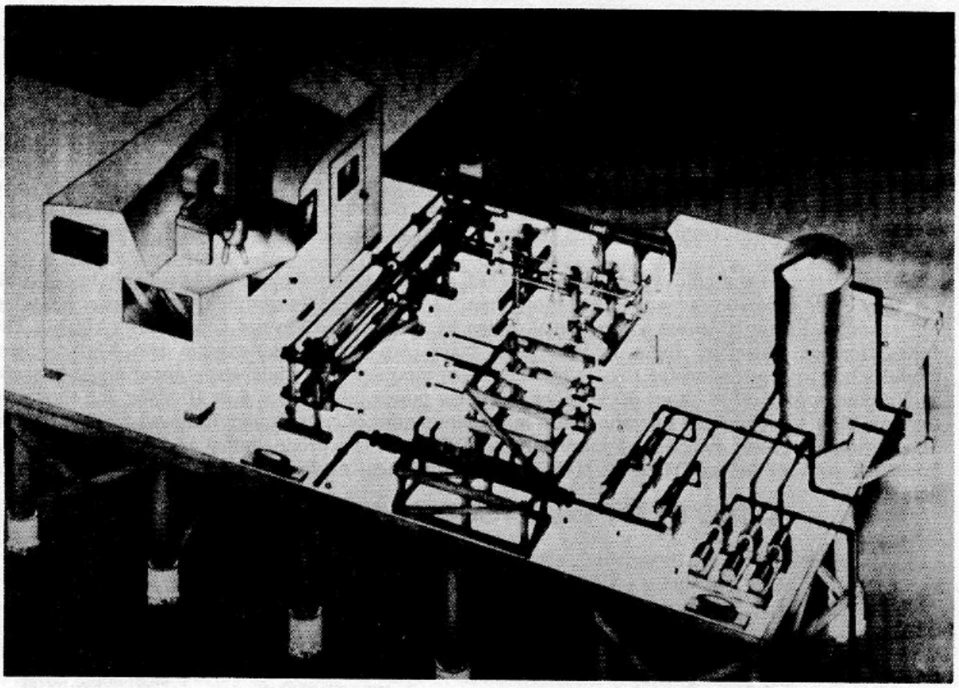


Figure 9. The OTEC Heat Exchanger Cleaning Test Facility Located at Panama City, Florida

Leakage Problems in Ammonia Systems

Calcareous deposits can form if there is leakage of ammonia into seawater. This process is associated with the resulting increase of pH. Similar deposits and/or corrosion could result on the working fluid side if seawater were allowed to leak into ammonia. Although efforts can be made to design OTEC heat exchangers that are leak-proof, a small percentage of heat exchanger tubes that leak can be tolerated by detecting such leaks and plugging the offending tubes.

Ammonia turbines will require special seals to contain the ammonia, and some additional development will probably be required to attain optimum sizes at maximum efficiency. Demisters for ammonia service pose no special problems. The ammonia working fluid must be kept free of water concentrations above 0.1 percent to prevent degradation of system performance (20) and to avoid corrosion. Accordingly, the ammonia closed cycle system will need to include provision for removing water from the ammonia.

TESTING PROGRAM

Component Test Facility

A floating engineering test facility is being developed for testing OTEC heat exchangers and other components at 1 MWe (40 MWt) in an ocean environment. Operation of this test facility, to be known as OTEC-1, is expected to begin in early 1980. The function of this testing will be to screen various candidate heat exchangers and other components under actual ocean conditions and thereby lead to improved performance and reduced costs for subsequent commercial OTEC plants. OTEC-1 will employ a cold water pipe about 2 meters (6 feet) in diameter at a depth of about 1000 meters (3300 feet). Tests of a shorter cold water pipe of comparable diameter are planned for the fall of 1978.

Pilot Plants

To provide performance evaluation of operating pilot plants of significant size, one or more modular system experiments at about 10 MWe are being considered for operation in 1982 or thereafter. Options being discussed for the modular experiments include a sea-based or land-based platform providing electricity to shore, and a grazing plant-ship platform to demonstrate the operation of a system that could manufacture ammonia at sea.

The platforms and cold water pipes for OTEC modular experiments would probably be oversize; i.e., they could ultimately accommodate more than the initial 10 MWe complement of power modules. For example, Figure 10 shows a conceptual design by the Applied Physics Laboratory (APL) of The Johns Hopkins University for a 20 MWe pilot plant ship that would contain two 5 MWe power modules but with provision for two additional power modules. A modular experiment might conceivably accommodate up to about 40 MWe capacity, via power modules of 5 or 10 MWe, and thus have the flexibility to commence operation with initial equipment of early design, followed by substitution or addition of power systems of more advanced design. The producibility and fabricability of a Lockheed concept for an OTEC 25 MWe shell-and-tube heat exchanger module has been analyzed (21)

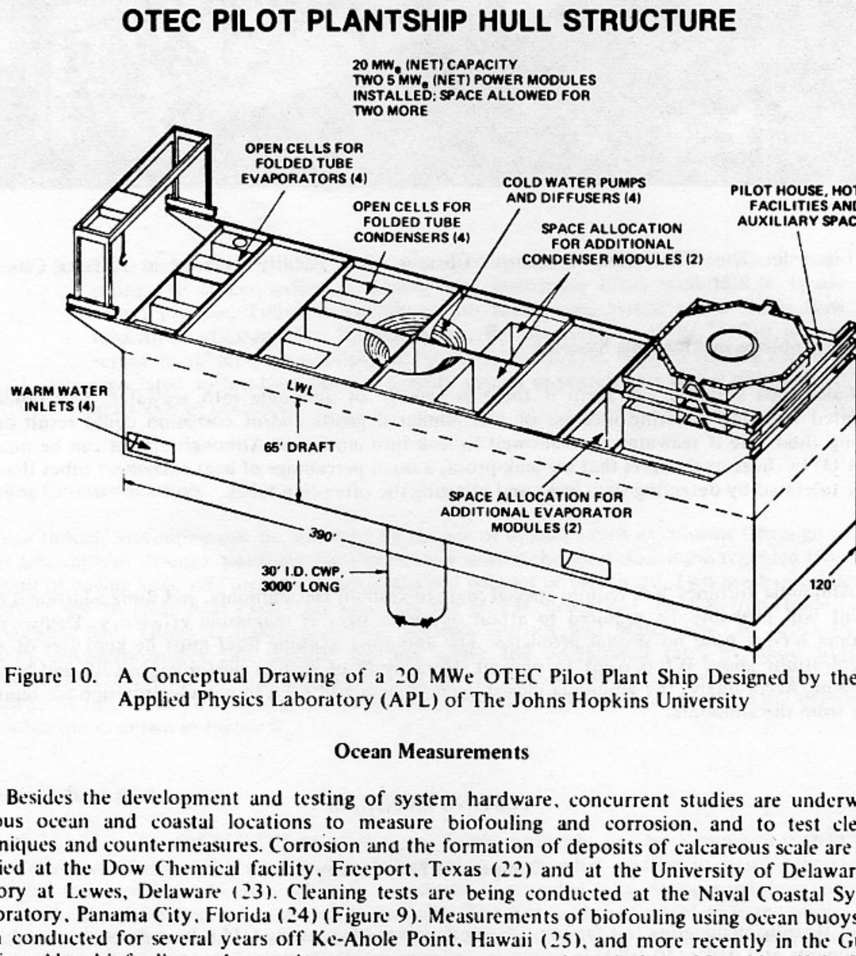


Figure 10. A Conceptual Drawing of a 20 MWe OTEC Pilot Plant Ship Designed by the Applied Physics Laboratory (APL) of The Johns Hopkins University

Ocean Measurements

Besides the development and testing of system hardware, concurrent studies are underway at various ocean and coastal locations to measure biofouling and corrosion, and to test cleaning techniques and countermeasures. Corrosion and the formation of deposits of calcareous scale are being studied at the Dow Chemical facility, Freeport, Texas (22) and at the University of Delaware laboratory at Lewes, Delaware (23). Cleaning tests are being conducted at the Naval Coastal Systems Laboratory, Panama City, Florida (24) (Figure 9). Measurements of biofouling using ocean buoys have been conducted for several years off Ke-Ahole Point, Hawaii (25), and more recently in the Gulf of Mexico. Also, biofouling and corrosion measurements were conducted (26), (27), (28) off the Virgin Islands on a U.S. Navy barge. Proposals for an OTEC Seacoast Test Facility are being considered. Such a coastal facility would utilize an intake pipe of about 30 cm (1 foot) diameter extending to depths of about 1000 meters (3300 feet) to study the biofouling characteristics of OTEC condensers, along with warm water intakes to simulate OTEC evaporators. Biofouling results up to this time have simulated conditions in OTEC evaporators only.

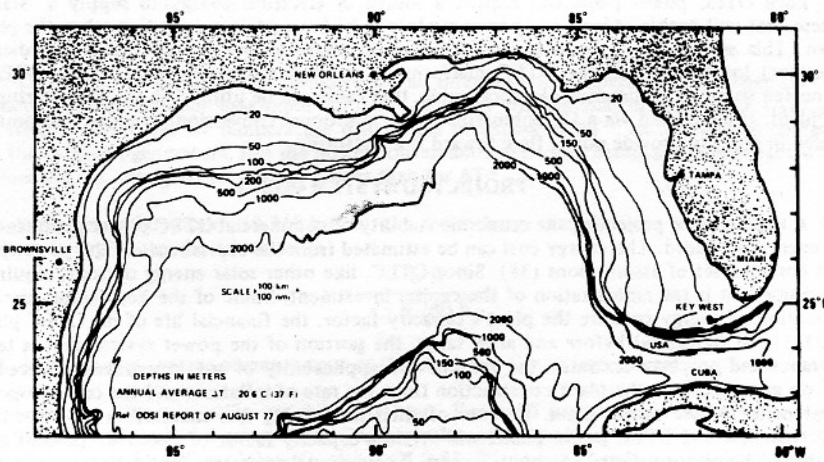
An important adjunct to the OTEC development program is the assessment of environmental and resource questions. Oceanographic data relevant to thermal resource and siting questions are being obtained from archival sources and through ocean measurements. Measurements are being conducted from both vessels and ocean buoys. A specialized Workshop on OTEC Resource and Environmental Assessment was held in June, 1977 in Florida (29).

An OTEC Environmental Development Plan (EDP) has been formulated by the U.S. Department of Energy (30) and an interagency OTEC environmental working group has been established. This working group includes representatives from the U.S. Environmental Protection Agency and the U.S. Department of Energy. The OTEC environmental and resource assessments concern the analytical, research and experimental activities in support of the development program and are to ensure minimization of possible OTEC environmental impacts and compliance with existing environmental regulations. Besides the possible effects of OTEC on the environment, these assessments provide engineering inputs so that possible impacts of the environment (such as sea condition) on OTEC design, siting, and operations can also be considered.

OCEAN SYSTEMS

OTEC power plants will usually be floating structures consisting of a power system contained by an ocean platform. The platform can be connected to shore via a submarine umbilical to convey its products in the form of AC or DC electricity, or via compressed air, liquid ammonia, and gaseous hydrogen. If an umbilical is utilized, then there will be a need for platform station keeping. This can be accomplished by anchoring and mooring, and/or dynamic positioning. On the other hand, if OTEC products are transported to market via barge or other vessel, the requirement for station keeping is less stringent.

If mooring is necessary, then optimum OTEC sites may be determined by a combination of thermal resource and mooring requirements. For example, it will be desirable to obtain a good heat sink, which is only attainable at depths of 700 to 1000 meters (about 2000 to 3000 feet). However, mooring technology may be limited to depths no greater than 2000 meters. Thus, the bathymetric zones where moored OTEC plants can operate will tend to be limited to depth ranges between about 700 to 2000 meters, as shown for example in the shaded areas of Figure 11.



OTEC RESOURCE REGION - GULF OF MEXICO

Figure 11. The shaded regions are ocean thermal resource zones in the Gulf of Mexico where annual average temperature differences greater than 20.6°C (38°F) are present overlying ocean bottom depths between 1000 and 2000 meters. (From reports of Ocean Data Systems, Inc.) (cf. Reference 51)

A key feature of the ocean system for floating OTEC power plants is an aqueduct known as the cold water pipe, or CWP. Although it has been suggested by Karig (31) that an OTEC system might avoid transporting the cold water by piping the vaporized working fluid (after its passage through the turbine) to a condenser mounted on the ocean bottom, this concept has been considered by a team headed by Lockheed (32) and found to be less attractive than using a cold water pipe.

Intakes for OTEC warm and cold water need to be screened to prevent the entry of fish and other marine biota that would otherwise damage themselves and/or plant operation if allowed to enter. Screens for OTEC plants have been studied by Nath *et al.* (33) and by Thomas and Bason (34). Similar screens to those required for OTEC are already in use for cooling water intakes at coastal power stations.

Large volumes of seawater–about 4 m^3/s per net MWe (6×10^6 gallons per minute per net 100 MWe)–need to be circulated via the cold water pipe, necessitating heavy duty seawater pumps. The cost of the warm and cold water pumps needed to circulate a total of about 8 m^3/s per net MWe (12×10^6 gallons per minute per net 100 MWe) probably constitutes about 10 percent of the total cost of the power plant and platform (35). The parasitic power requirement for circulating the cold water is mainly associated with the need to overcome the pressure head resulting from the variable compressibility and variable density of water as a function of depth. This power requirement consumes about 10 to 20 percent of the gross power output of the plant.

For commercial-size (~400 MWe) OTEC systems relying on a submarine electrical cable to transmit power to shore, certain advancements will be necessary in the state-of-the-art for design and deployment of electrical cables. Studies of OTEC bottom cables and OTEC riser cables are presently being conducted by the Pirelli and Simplex cable companies, as reported by Morello (36) and by Pieroni *et al.* (37), respectively.

For OTEC plants located out to about 30 km (about 20 miles) from shore, AC cables can be utilized. At greater distances, the marginal costs for power-factor compensation of long submarine AC cables for inductive and capacitative effects become excessive compared to the inversion and conversion costs incurred when resorting to high voltage DC submarine transmission cables. For most island applications, and for some mainland applications, the ocean thermal resource is within the 30 km (20 mile) tradeoff distance, so that AC submarine cables will prove more economic. However, much of the ocean thermal resource is located at distances from shore exceeding 30 km, hence DC transmission will be required. Present projections indicate that the costs of such transmission will probably limit DC submarine cable transmission to distances of about 300 km (200 miles) from shore.

Each OTEC power plant will require a source of electrical energy to supply a "startup" subsystem that will enable at least one power module to be brought into operation when the plant is shut down. This system could be energized from an auxiliary power source (such as a diesel-electric generator) located aboard the OTEC platform or on an auxiliary platform. If the OTEC plant is connected to an AC submarine electrical cable, that cable can be utilized to transmit startup power to the plant. If connected via a DC submarine cable, additional conversion/inversion equipment will be needed in order to provide power flow toward the platform.

PROJECTED SYSTEM COSTS

A key factor in projecting the economic viability of commercial OTEC power plants is the cost of the energy produced. The energy cost can be estimated from the capital cost of the power plant based on a complex set of assumptions (38). Since OTEC, like other solar energy options, requires no fuel, the major cost is the amortization of the capital investment. Some of the key factors that enter the calculation of energy cost are the plant's capacity factor, the financial life of the OTEC plant, its tax life, the cost of capital before and after taxes, the portion of the power system that is taxable, the insurance and property tax rates, the amount and applicability of any investment tax credit, the tax rate on gross receipts, the plant construction time, the rate of inflation, and the cost of operation and maintenance of the power plant. Because of their modularity and standardization, it is likely (39), (40) that baseload OTEC power plants will attain a capacity factor of about 85 percent and will be capable of being constructed in about 3 years. Their annual operation and maintenance (O&M) costs are variously estimated at about 1.5 percent of the capital investment.

The economics of OTEC are sometimes confused with concern about its low net conversion efficiency, which is about 2.5 percent for temperature differences of 20°C. The theoretical Carnot efficiency of about 7 percent is reduced by various factors, especially the OTEC requirement for parasitic power for pumping its cold water supply. The main consideration, since there is no fuel cost, is to optimize the net efficiency at a resulting life-cycle energy cost that is within the competitive cost range of other energy options.

Although OTEC power plants will provide steady outputs throughout the day and from day to day, plant output will vary seasonally, as shown for example in Figure 12. This variation for a given plant will depend (41) sensitively upon the temperature difference, ΔT, of the input warm and cold water supplies. The plant capital cost, C, will depend inversely upon the design temperature difference, ΔT^*, through the relationship

$$C \propto (\Delta T^*)^{-k}$$

where $k \approx 2.5$.

Seasonal Variation of Utility Loads vs Projected OTEC Power Plants at Tampa

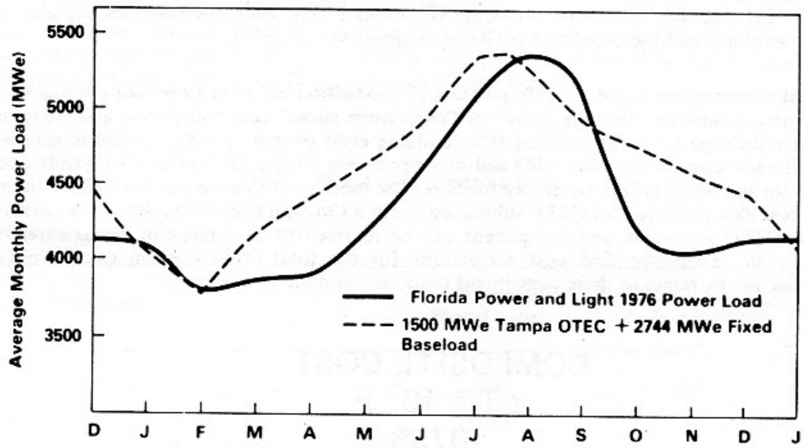


Figure 12. A comparison of the 1976 seasonal variation of electrical load served by the Florida Power and Light Company with the combination of the projected seasonal variation of 1500 MWe of OTEC capacity combined with 2744 MWe of fixed baseload capacity. The temperature variations used to calculate seasonal OTEC power variations were obtained from Ocean Data Systems, Inc. analyses. (cf. References 51 and 53)

An OTEC power plant can be designed for an intermediate temperature difference ΔT^* somewhere between the seasonal maximum ΔT (ΔT_{max}) and the seasonal minimum ΔT (ΔT_{min}). Of course, to take advantage of temperature differences in excess of ΔT^*, certain system components such as the turbines, generators, and the power conversion/inversion/transmission equipment will need to be oversized, i.e., designed for ΔT_{max} rather than for ΔT^*.

For each year of operation (8,760 hours), at a fixed charge rate, R, and a capacity factor, C_f, the energy cost, E, is given by the relationship

$$E = \frac{C\,R}{C_f\, 8{,}760\, \overline{P_o}},$$

where $\overline{P_o}$ is the annual average power output of the plant and C is its capital cost.

E is usually stated in mills per kilowatt hour. For a 30 year lifetime, allowing a 7 percent investment tax credit, and 1.5 percent for O&M, a value of R of about 15.7 percent is derived (38). For a capital cost of \$1,500 per kilowatt, at a C_f of 0.85, E is about 32 mills per kilowatt hour. OTEC capital cost targets for 400 MWe power plants range from about \$1,500 to \$1,900 in 1978 dollars for electrical energy delivered to Gulf Coast ports such as Tampa and New Orleans, and about \$1,200 to \$1,700 for United States islands such as Hawaii and Puerto Rico. (These amounts would be about 25 percent less in 1975 dollars, which have frequently been used for energy cost intercomparisons.) The corresponding energy costs range from about 32 to 41 mills per kilowatt hour and 26 to 36 mills per kilowatt hour, respectively, in 1978 dollars.

Conceptual baseline studies by Lockheed (32) and TRW (39) in 1975 led to conservative, state-of-the-art estimates of OTEC system costs for the baseline commercial power plants considered by those organizations. These cost estimates differed considerably from those obtained previously by OTEC proponents (40). The explanation for this discrepancy was that the proponents, in formulating their own cost estimates, had assumed certain engineering improvements and innovations had already been achieved. Lockheed and TRW in fact pointed to significant cost savings that could be achieved through an OTEC engineering development program, which they both independently recommended should be pursued by the United States Government.

Since 1975, additional system cost estimates can be projected as the result of the more detailed succeeding studies. In particular, power system costs are being considered through three concurrent contracts with Lockheed, TRW and Westinghouse, who are examining candidate OTEC power systems utilizing competitive varieties of shell-and-tube heat exchanger designs (41), (42), (43). Concurrently, three platform studies by Gibbs and Cox (44), M. R. Rosenblatt and Son (45), and Lockheed (46) obtained cost estimates for several candidate OTEC platforms. Also, system costs and platform costs for their ammonia plant ship concept are being obtained by APL (47).

Cost estimates are based on extrapolating to production units the projected economies expected to be achieved through "learning curve" or "experience curve" cost reductions, and are typically the result of estimating the costs resulting from building eight or more plants. Critical integration of the results of early cost studies (40), (48) and of more recent studies (38), (49), (50), yields a composite of costs for providing OTEC electricity to shore. The more recent cost estimates include the results to date of cost data projected for OTEC submarine bottom (36) and riser (37) cables. The costs projected for each OTEC subsystem and component can be represented as a range of values extending from optimistic to pessimistic, and cost projections for the total OTEC system can be obtained by aggregating the extremes of these constituent costs, as was done in Figure 13.

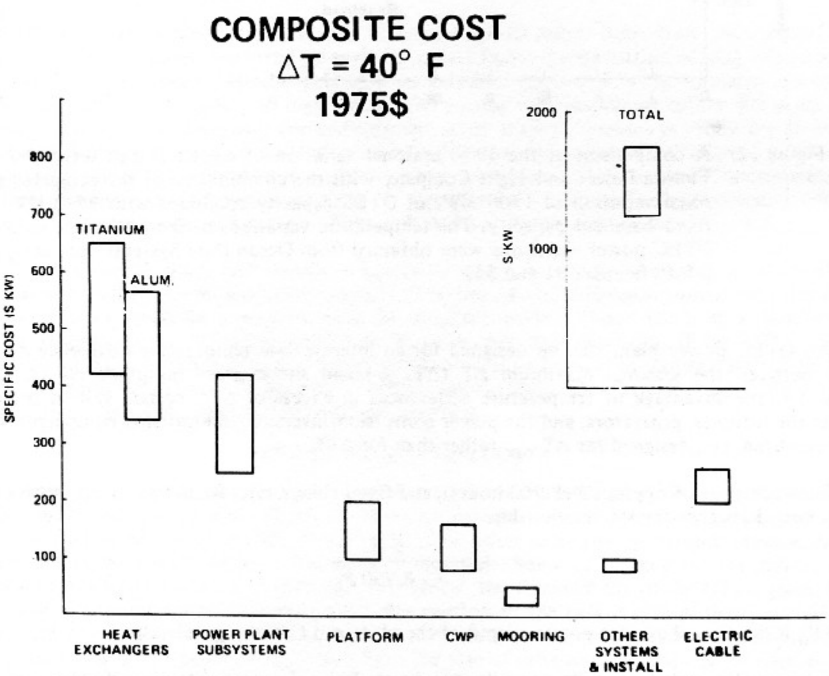


Figure 13. Ranges of projected capital costs for OTEC subsystems and total systems utilizing constant 1975 dollars. Electrical cable costs were estimated for DC cable links of about 130 to 230 kilometers (80 to 140 miles).

Note in Figure 13 that the initial cost of a system with aluminum heat exchangers might well be several hundred dollars per kilowatt smaller than the system cost of a system with titanium heat exchangers. However, it remains to be established whether an aluminum system can be qualified from the standpoint of corrosion resistance to provide a longevity comparable to that of titanium. If so, then the relatively smaller initial acquisition cost would represent a considerable advantage for aluminum versus titanium. If not, then the aluminum exchangers would have to be replaced one or more times during a 30 year period, leading to higher life cycle costs relative to titanium. The cost projections for heat exchangers are also complicated by the need to trade-off optimum augmentation of heat transfer with the associated cost effectiveness of achieving such enhancements.

The system costed in Figure 13 includes about $250 per kilowatt for electrical transmission to points in southern United States from the Gulf of Mexico. For United States islands, the cable transmission costs will range from about $50 to $100 per kilowatt. A breakdown of the likely materials from which an OTEC power plant would be constructed is shown (49) in Figure 14. This breakdown indicates a weight of about 1350 kilogram per kilowatt (3000 pounds per kilowatt). At a cost of $1,500 per kilowatt, this would require the fabricated cost of the plant to be $1.10 per kilogram ($0.50 per pound). To achieve such a target, the use of reinforced concrete as a key hull ingredient seems well advised as compared to steel. Automobiles, it should be noted, have long been mass produced at a cost of about $2.20 per kilogram ($1 per pound).

OTEC Materials Breakdown

Material	Bulk Weight (Short Tons)	Normalized Weight (ST/MW)
Concrete	333,000	900
Rebar	165,000	450
Structural Steel	28,000	76
Aluminum Sheet/Tube	8,000	22
Copper *	7,600	21
Alloying Agents (MG,MN,CR,ZN)	800	2
Total	~ 540,000 ST	~ 1470 ST/MW

* Includes Transmission Lines (3)

Figure 14. Estimates of materials requirements for an OTEC power plant off Tampa, Florida providing a maximum of about 368 MWe to shore. The numbers of short tons correspond to 10% fewer metric tons (tonnes). (Reference 49)

The range of targeted OTEC energy costs for baseload power is comparable to projected costs for other baseload power sources (such as coal and nuclear) in the 1990 to 2000 Gulf Coast market for electricity. However, in United States island markets (e.g., Hawaii and Puerto Rico), OTEC power plants could even sooner achieve costs that are less than the projected costs of oil-derived electricity. This is the case even for small OTEC power plants. These qualitative statements are illustrated in Figure 15.

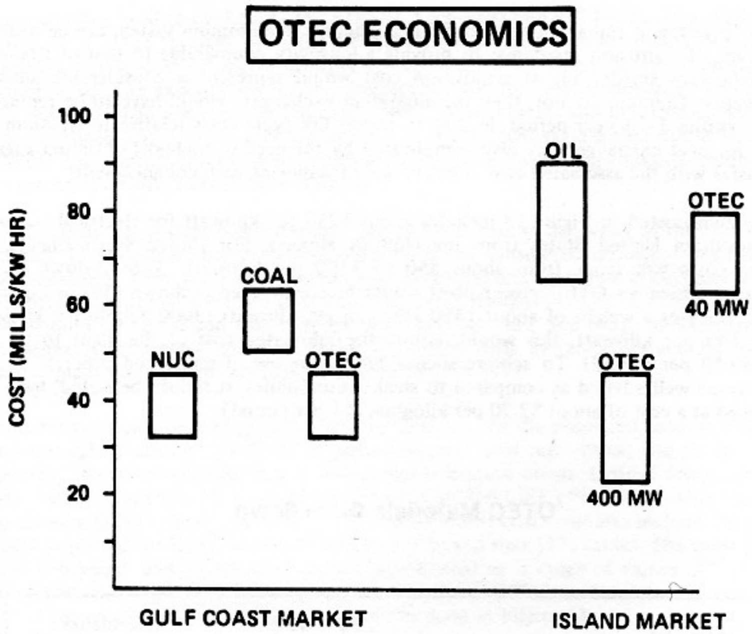


Figure 15. Ranges of projected OTEC energy costs estimated for year 2000 in constant 1978 dollars compared to ranges of projected energy costs for baseload electricity derived from coal, uranium, and oil for Gulf Coast and U.S. island markets. Note the variation in energy cost estimated at two different OTEC plant sizes for the island markets. OTEC plant sizes for the Gulf Coast market were assumed to be 400 MWe.

An example of cost breakdown estimates in 1978 dollars per kilowatt for production units of 400 MWe OTEC power plants is provided for Gulf Coast points in the following table, utilizing Lockheed estimates (46), for a ship platform and a composite estimate from results (41), (42), (43) of the power system development contractors:

ΔT = 22°C (40°F)	Titanium Heat Exchangers	Aluminum Heat Exchangers
Heat exchangers	650-850	450-650
Power plant subsystems	450	450
Platform	200	200
Cold water pipe	100	100
Mooring	50	50
Electrical cable (to Gulf Coast)	250	250
Other systems	50	50
TOTAL:	1750-1950	1550-1750

These costs range from 1400-1550 and 1250-1400, respectively, when measured in 1975 dollars. The power plant subsystems in the above table include turbines and generators, each at about $50 per kilowatt, and seawater pumps at about $100 per kilowatt.

RESOURCE POTENTIAL

The global ocean thermal resource can be mapped, as shown in Figures 16A and 16B, in terms of annual average temperature differences between the surface waters and the water at a depth of 1000 meters (3300 feet). The most valuable ocean thermal resources should probably offer average temperature differences of 20° C (36° F) or greater. The contours of greatest interest in Figures 16A and 16B are therefore those for 20° C, 21° C, 22° C, 23° C, and the nominal 24° C contour, which corresponds to temperature differences of 24° C or larger. A considerable region of the globe thus appears advantageous for OTEC exploitation, including many locations accessible to land via submarine cable and extensive ocean areas where OTEC plant-ships could produce energy-intensive products at sea. This region happens to coincide geographically with the locations of numerous developing nations, and if commercially viable could provide a substantial addition to world energy resources. For applications where mooring of the plant is required, there are practical upper limits of about 2000 meters for tolerable mooring depths. In such cases, sites of interest would be limited to regions where ocean depths ranged from about 1000 to 2000 meters.

ΔT(°C) BETWEEN SURFACE AND 1000 METER DEPTH

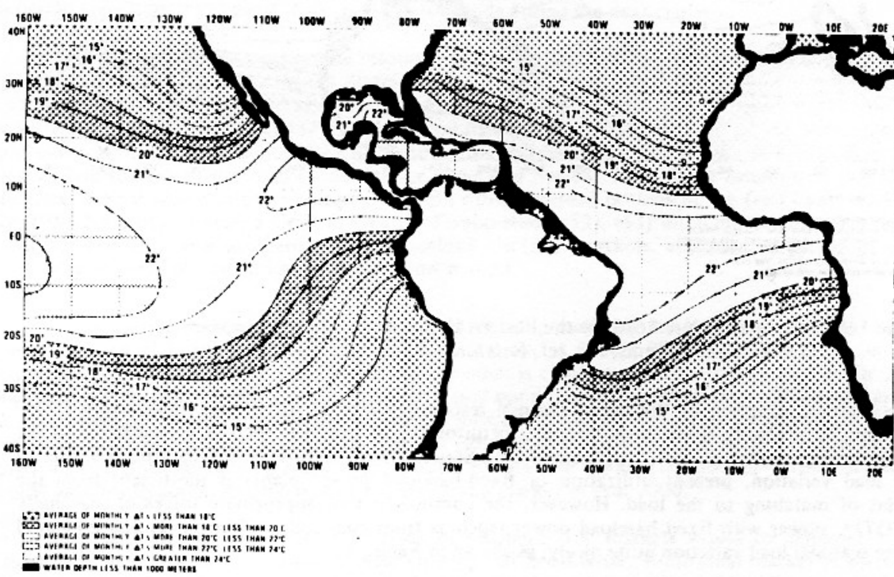


Figure 16A. Contours for stated annual average temperature differences between the ocean surface and depths of 1000 meters for the Western Hemisphere. The most promising ocean thermal resources are contained within the areas having an annual average temperature difference of 20°C or larger.

Although the ocean thermal resource at a given location is quite stable from day to day, there is a seasonal variation of the resource. The amplitude of variation increases with distance of departure north and south of the equator. There are substantial ocean thermal resources in the Gulf of Mexico available to Continental United States via submarine electrical cable. Also, United States islands such as Puerto Rico, the Virgin Islands, Guam and the Hawaiian Islands have excellent ocean thermal resources very close to their shores.

Potential sites in the Gulf of Mexico for providing electricity to United States shores are included in the shaded area of Figure 11, which indicates the oceanic region having annual average $\Delta T \geq 20.6°C$ (37°F) at ocean depths between 1000 and 2000 meters. It would probably be preferable to use as a statistic the root-mean-square (RMS) ΔT rather than the average ΔT, since the net power obtainable from a given OTEC plant varies with $(\Delta T)^2$ in the neighborhood of the plant's design temperature. However, in practice these statistics differ only slightly, i.e., the RMS ΔT exceeds the average ΔT by about 0.2°C (0.4°F).

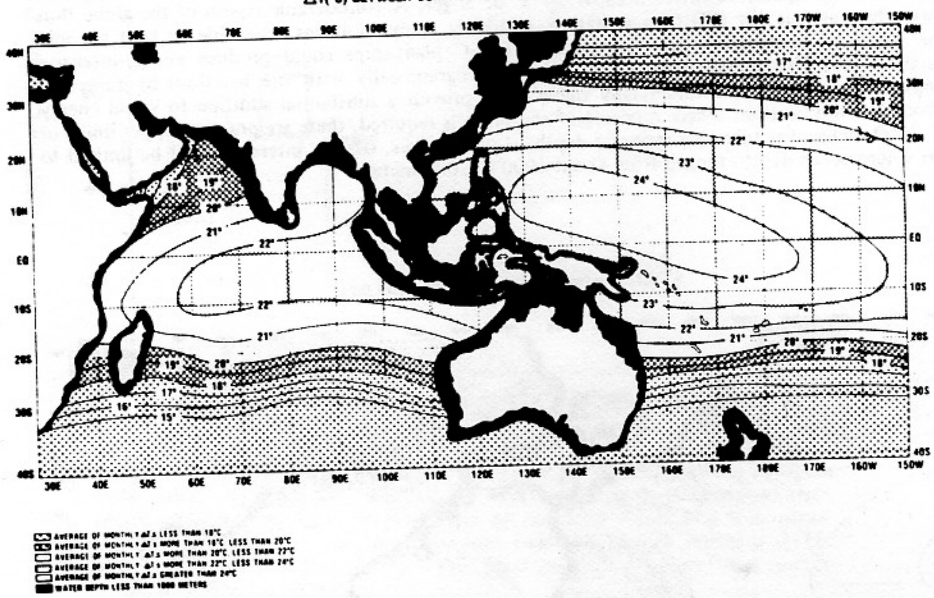


Figure 16B. Same as Figure 16A, for the Eastern Hemisphere. These maps were derived by Ocean Data Systems, Inc. (cf. Reference 51)

The seasonal variation of the ocean thermal resource, hence of the output power from OTEC power plants, is probably quite advantageous, fortuitously, at least for providing electricity to the seasonally varying electrical load in southern United States. There, because of the significant winter to summer load variation, present utilization of fixed-baseload power plants is inefficient from the standpoint of matching to the load. However, the combination of appropriate mixes of seasonally varying OTEC power with fixed baseload power (such as from coal and nuclear power plants) would match the seasonal load variation quite nicely, as shown in Figure 12.

OTEC MARKETS

Besides the research and development activities described above, the OTEC Program Office is also concerned with programmatic questions associated with the marketability of OTEC electricity and energy-intensive products. Those questions revolve about the projection of costs for commercial OTEC systems, and relate to potential markets, market penetration, and legal, institutional and financial matters.

The introduction of OTEC technology into the marketplace will not necessarily occur simply as a consequence of its successful demonstration and achieving competitive cost goals. There are numerous factors that will affect OTEC marketability and commercialization. In particular, this technology is confronted with a situation more complex institutionally than most other solar energy technologies, in that most of the products derived will be manufactured beyond state boundaries. Besides creating questions as to who will be the owner/operators of OTEC plants and plant ships, and how OTEC capital formation will occur, there is the key problem associated with at-sea operation concerning the prevailing legal regime. It will clearly be essential to resolve this problem in a fashion conducive to the attractiveness and legal stability of OTEC commercial operation. However, the fact that the offshore oil industry and the offshore nuclear industry have made considerable progress in solving comparable problems is somewhat encouraging.

From a global standpoint, OTEC represents a substantial potential increment of world energy supply. In particular, it could provide (cf. Figures 16A and 16B) large amounts of electricity via submarine cable to many nations in tropical and subtropical regions, up to about 25° of latitude on either side of the equator. The prime ocean thermal resource is roughly bounded by the 20° C contour of Figures 16A and 16B, and would of course provide considerable potential for the manufacture of energy-intensive products beyond the regions readily accessible to shore via cable.

From a more parochial viewpoint, it is clear that considerable ocean thermal resources are available to the United States. Besides the prime areas in the Gulf of Mexico shown in Figure 11, there are excellent ocean thermal resources located a few kilometers off U.S. islands such as Hawaii, Puerto Rico, Guam, the Virgin Islands, American Samoa, and Micronesia. The total amount of OTEC power that could be supplied via cable to Gulf Coast locations such as New Orleans and Tampa from the shaded areas of Figure 11 is conservatively estimated (51) at upwards of 200 GWe, and perhaps as high as, or higher than, 600 GWe. This estimate assumes that the constraint is a significant degradation of the ocean thermal resources flowing into those regions. This power potential is comparable to, or greater than, the electrical market expansion projected for southern United States for at least the next twenty years. Also, the ocean thermal resource in the vicinity of U.S. islands is measured in the tens of gigawatts, and far exceeds the power required to replace existing production and to satisfy the potential incremental electrical markets in those islands during the next century.

Thus, the available ocean thermal resources in the Gulf of Mexico can serve a potentially growing electrical market in southern United States commencing between 1985 and 2000. This assumes that cost reductions can be realized associated with traversing the learning (or experience) curve through manufacturing a group of initial OTEC plants and then entering a "production" phase. It also assumes that the cost of energy from these production units will be comparable to the cost of energy from competitive sources of baseload electricity; i.e., coal and nuclear. Making the assumption that OTEC electrical energy would become competitive with other baseload options in the Gulf Coast market in the 1985-2000 time frame, a General Electric Tempo study (52), (53) intercompared growth projections for the U.S. and southern regional baseload electrical markets, and then projected plausible penetrations of OTEC into the southern regional market.

GE Tempo utilized two basic scenarios for electrical growth for the U.S. as a whole and for the three southern U.S. regional reliability councils (known as SERC, SWPP, and ERCOT). One is a fairly rapid rise, projected by GE Tempo, and the other is a slower growth rate projected by Dr. Alvin Weinberg of the Institute for Energy Analysis. Based upon these two growth rates, GE Tempo arrived at three possible OTEC implementation rates, shown by the set of curves in the lower part of Figure 17 for high, intermediate and low market penetrations. These projections lead to a total OTEC baseload contribution ranging from 6 to 35 GWe by the year 2000. The most optimistic projection would amount to about 30 percent of the incremental market in year 2000.

Those scenarios assume that penetration of southern U.S. markets would be achieved by DC cables into locations such as Tampa, New Orleans and Brownsville. Additional market penetrations would be realized by short AC cables into U.S. island locations such as Puerto Rico, Hawaii and Guam. From southern U.S. locations, OTEC energy could be wheeled inland via high voltage transmission lines. Cable runs of about 80 nautical miles will be required to reach locations such as New Orleans, and about 140 nautical miles to reach locations such as Tampa and Brownsville. According to the GE Tempo study (53), OTEC power wheeled inland from Gulf Coast submarine cable terminals could penetrate the market at various distances, depending upon the initial cost of OTEC energy at shore, the cost of high-voltage DC overland transmission, and the costs of competitive baseload electricity. Good ocean thermal resources are also situated within several miles of the west coast of Mexico, and just south of Baja California. Thus, OTEC power could readily become economic for Mexican utilization and potentially for export to U.S. locations such as southern California and Texas.

U.S. islands, such as Puerto Rico and Hawaii, will probably constitute excellent early markets for OTEC electricity. These markets will likely be competitive in cost immediately, even for the first commercial OTEC plants. The key reason for this statement is that the existing electricity supply on U.S. islands is largely derived from imported oil. Also, short AC cables will suffice. A comparison of costs for oil-derived and OTEC-derived electrical energy is shown for Hawaii in Figure 18 for the mid-1980's. The cost of the first 250 MWe OTEC power plant is estimated at $2800 per kilowatt in deriving the first OTEC point plotted, followed by learning-curve cost reductions estimated at 90 percent for each doubling of the cumulative number of OTEC power plants.

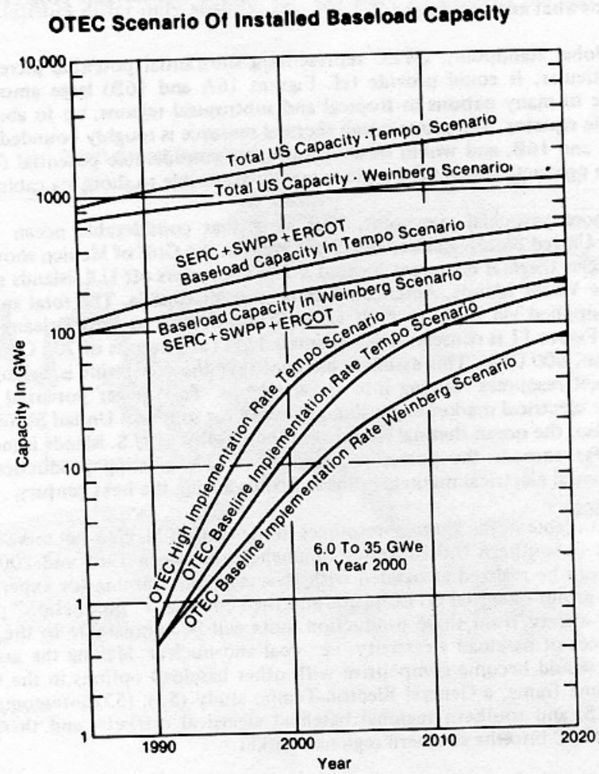


Figure 17. Some scenarios for baseload electricity utilization in the United States and in Southern United States, as derived by General Electric Tempo (from Reference 53), along with projections of possible OTEC market penetrations in the Southern States. The abbreviations SERC, SWPP, and ERCOT refer to the southern utility regions defined by the regional electric utility reliability councils.

In principle, much of the present utilization of oil to produce electricity could be replaced by OTEC power production at U.S. islands, especially as existing gas turbines are amortized and phased out. Each megawatt of oil-derived electricity is equivalent to about 40 BBL/day of oil displacement, hence the eventual utilization of 2000 MWe of OTEC electricity in Puerto Rico, for example, would save about 80,000 barrels of imported oil (costing about one million dollars) per day. The achievement of this "island strategy" of market penetration and the associated cost reductions achieved could then enable penetration of the Gulf Coast market. Figure 19 is a qualitative representation of the sort of cumulative market penetration that might be achievable in the U.S. island, Gulf Coast and international markets in the 1985-2010 time frame.

Consideration must be given in such scenarios to production constraints, including requirements for material and energy resources. In particular, if aluminum alloys were to be qualified for use in OTEC heat exchangers, then the supply of aluminum would probably be quite adequate even if 5 or even 10 GWe of OTEC power capacity were added annually. On the other hand, if titanium were employed for OTEC heat exchangers, then a considerable expansion of the present U.S. production capacity for titanium would have to be provided. Fortunately, there is an abundant supply of titanium ores. Similarly, significant numbers of OTEC power plants requiring electrical cables would seriously tax world submarine electrical cable production capabilities, which would have to be greatly augmented.

From a net energy standpoint, the energy payback time (i.e., "breeding time") for an OTEC plant seems favorable. Even though considerable aluminum would be required, for example, it is easy to calculate that at about 10 kwh per pound of aluminum it would take about one month of energy

HAWAII
COSTS OF ELECTRICITY FROM OIL AND 250 MWe OTEC PLANTS (1975 DOLLARS)

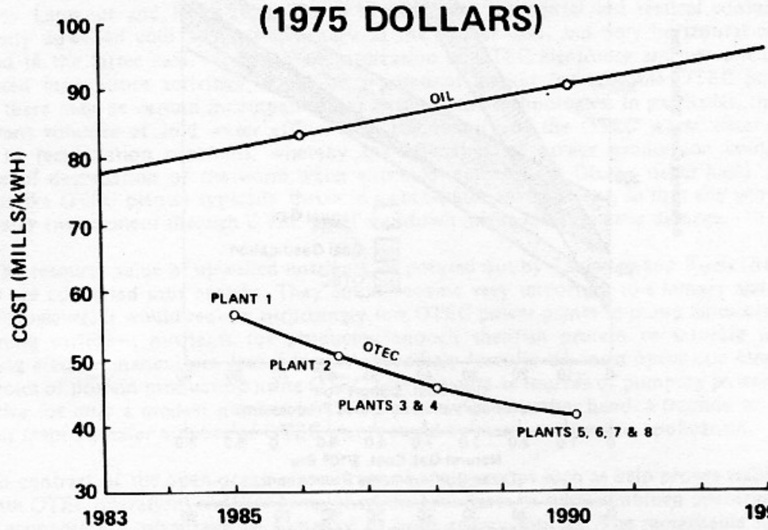


Figure 18. Comparison (in constant 1975 dollars) of baseload electrical energy costs projected for Hawaii for oil-derived electricity with energy costs for electricity derived from 250 MWe OTEC plants. The first OTEC plant is estimated to cost $2800 per kilowatt, with a 90% learning-curve factor applied for each doubling of the total number of such plants.

CUMULATIVE OTEC MARKET PENETRATION

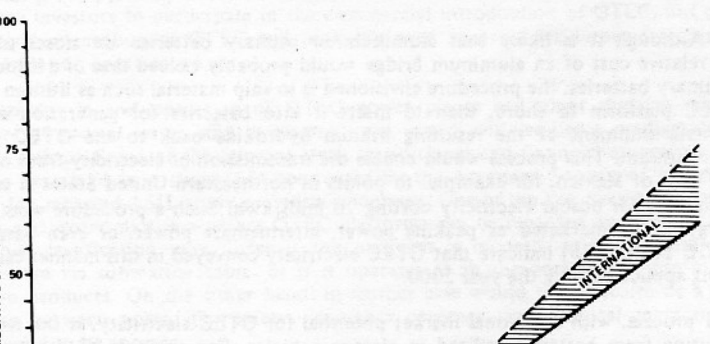
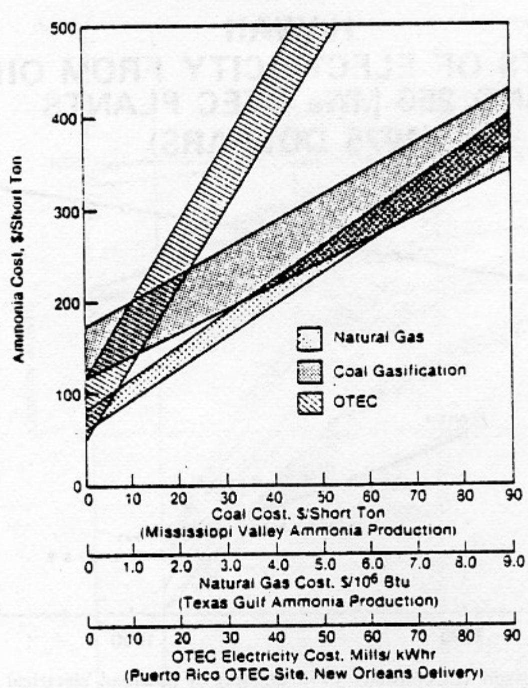


Figure 19. A qualitative projection of the possible evolution of cumulative OTEC market penetration in U.S. islands, Gulf Coast, and international markets. This projection was for baseload electricity only.

Ammonia Cost As A Function Of Feedstock Cost
($/Short Ton, 1976 Dollars)



Source: Institute Of Gas Technology

Figure 20. A comparison of ranges of cost of ammonia derived from coal, natural gas, and OTEC electricity, as measured in constant 1976 dollars (from Reference 53). The costs per ton can be converted to costs per tonne by multiplying by 1.1; natural gas costs in dollars per million Btu correspond to about the same costs measured in dollars per trillion joules.

development. Although it is likely that aluminum/air primary batteries are closer to commercial readiness, the relative cost of an aluminum bridge would probably exceed that of a lithium bridge. In the case of primary batteries, the procedure envisioned is to ship material such as lithium in bulk form from the OTEC platform to shore, then to insert it into batteries for generation of electricity, followed by bulk shipment of the resulting lithium hydroxide back to the OTEC platform for reconversion to lithium. This process would enable the transmission of electricity from ocean thermal sources in the Gulf of Mexico, for example, to points in northeastern United States at costs of about 80 to 100 mills/kwh for busbar electricity costing 20 mills/kwh. Such a procedure would enable this electrical energy to be marketed as peaking power, intermediate power, or even baseload power. Estimates by GE Tempo (53) indicate that OTEC electricity conveyed in this manner can be competitive for peaking applications by the year 2000.

A related process, with additional market potential for OTEC electricity, is the reprocessing of chemicals resulting from batteries utilized in electric vehicles. For example, if lithium/air batteries were utilized in the large fleet of electric automobiles that is projected for year 2000 by many observers, then the lithium hydroxide could be recycled to lithium on OTEC plant ships.

There are two possible OTEC byproducts that may be marketable; these byproducts are 1) fresh water and 2) shellfish, kelp or other food/energy crops resulting from open-ocean or onshore mariculture utilizing the nutrients upwelled in the cold water circulated through OTEC condensers. The intrinsic economics of OTEC energy production may well be benefited in certain instances from such byproduct manufacture. However, the market possibilities are sensitive to geography and to many uncertainties, especially in the case of mariculture.

The cost of transporting fresh water produced as an adjunct to OTEC power production would be substantial, except for on-shore or near-shore applications. Accordingly, it is probable that the marginal cost-effectiveness of manufacturing fresh water as an OTEC byproduct will not be favorable for floating OTEC power plants at significant distances from shore.

The technology for open-ocean mariculture of protein crops, such as shellfish, will probably differ from the technology of open-ocean mariculture of energy crops, such as kelp, according to a study by Laurence and Roels (61). This is because both horizontal and vertical containment of the artificially upwelled cold water is necessary in the former case, and only horizontal containment is required in the latter case. Although the utilization of OTEC electricity and upwelled nutrients for associated mariculture activities would be a potential market for available OTEC power and cold water, there may be certain incompatibilities between the technologies. In particular, the retention of significant volumes of cold water effluents in the vicinity of the OTEC warm water intakes might result in recirculation problems, whereby the efficiency of power production could be reduced because of degradation of the warm water entrance temperature. On the other hand, plants such as kelp (unlike OTEC plants) typically thrive in a cold-water environment, so that any protracted loss of cold-water environment through OTEC plant shutdown might result in crop damage.

The resource value of upwelled nutrients, as pointed out by Laurence and Roels (61) is very great if they are converted into protein. They could become very important to a hungry and malnourished world. However, it would require surprisingly few OTEC power plants to pump amounts of cold water containing sufficient nutrients for producing enough shellfish protein to saturate world markets, assuming a viable mariculture technology. Accordingly, even in the most optimistic case, the marginal economics of protein production using OTEC power plants as sources of pumping power would appear attractive for only a modest number of OTEC plants. On the other hand, a fraction of the cold water effluent from a greater number of OTEC plants could be marketed for this application.

In contrast, if the open-ocean mariculture of energy crops such as kelp proves viable and compatible with OTEC operation, and *vice versa*, then the synergism of such combined operations may indeed prove economically advantageous someday to both energy sources. The remarkable fact that OTEC power production intrinsically provides an artificial upwelling of nutrients and a source of electricity for distributing those nutrients within open-ocean mariculture farms still does not justify making an exception to the author's maxim that "one should not prematurely combine immature technologies".

Finally, we consider the legal, institutional and financial questions confronting the commercialization of OTEC technology. These are probably much more severe, in many respects, than related problems associated with the introduction of other new energy technologies. In particular, it is by no means clear who will be the owner/operators of OTEC power plants and plant ships. Commercial OTEC ventures will necessitate considerable capital formation and a favorable investment climate. On the one hand, it will probably require (62) significant federal incentives and assumption of risks to encourage private investors to participate in the commercial introduction of OTEC, but on the other hand, such federal promotion of OTEC will probably need to avoid regulatory features that could make such participation unattractive.

The investment in and operation of OTEC power plants and plant ships in territorial seas, economic zones of coastal states, and in international waters will require a predictable and stable applicable legal regime. Some of the relevant legal, institutional and financial aspects of OTEC plant operation were examined in a study (63) conducted by the American Society of International Law (ASIL). There is a renewed ASIL study presently underway. One of the key considerations concerning applicable law and economics is whether OTEC platforms can be regarded as "vessels" from a legal standpoint. This classification may differ if the platform is moored, as in the case of providing electricity to shore via submarine cable, or if it operates as an unmoored plant ship manufacturing energy-intensive products. On the other hand, in neither case would the platform be a vessel in the sense of plying between ports. The safety, insurance coverage, and physical protection of OTEC platforms will need to be ensured.

The facilitation of OTEC commercialization and ownership will require an intricate institutional structure, generically described by Ezra (64) as a "technology delivery system". Some of the scenarios for OTEC commercialization have been analyzed and discussed by Naef (65), who also identifies possible OTEC owner/operators. Entrepeneurial arrangements that may evolve include completely private ownership of OTEC facilities, public ownership, or mixed public and private ownership. A study of possible domestic entrepeneurial alternatives and the legal aspects and pros and cons of each is being conducted by the law firm of Tefft, Kelly and Motley. One such arrangement which they examined in this connection was recently reported (66). The relative attractiveness of a capital-intensive option such as OTEC as an investment opportunity in an era where the demand for capital will strongly exceed its supply will probably be a strong factor in determining its rate of market penetration, perhaps outweighing questions of how cost-competitive are its products.

The prospects for OTEC technology thus depend both on economic factors and on institutional factors. Both sets of factors will need to be satisfactorily resolved before OTEC commercialization can occur (67). If and when this is achievable. the ocean thermal resource could provide the world a new source of renewable energy having substantial potential to help meet growing worldwide demands for additional energy supplies. In a global climate where aspirations for energy are beginning to exceed the plateau in the supply of depletable energy reserves. OTEC-derived electricity and energy-intensive products. by increasing world energy supply. could help reduce foreseeable polarizations between nations over energy resources.

REFERENCES

1. Homma, T., "Conceptual Design and Economic Evaluation of OTEC Power Plant in Japan," Proceedings of the Fifth OTEC Conference (Miami. Florida. February 20-22. 1978), T. Nejat Veziroglu, Editor. University of Miami, 1978.

2. "Ocean Thermal Energy Conversion," September 1977. Association Européene Océanique (EUROCEAN), Monaco.

3. "OTEC Program Summary," ERDA 76-142, October 1976, U.S. Energy Research and Development Administration, Washington, D.C.

4. "OTEC Program Summary." DOE/ET-0021/1, January 1978, U.S. Department of Energy, Washington, D.C.

5. d'Arsonval, A., "Utilisation des forces naturelles. Avenir de l'électricité." La Revue Scientifique, 1881, pp. 370-372.

6. Claude, Georges, "Power from the Tropical Seas," Mechanical Engineering, Vol. 52, 1930, pp. 1039-1044.

7. Watt, A. D., Mathews, F. S., and Hathaway, R. E., "Open Cycle Ocean Thermal Energy Conversion: A Preliminary Engineering Evaluation," ALO/3723-76/3, December 1977, Colorado School of Mines, Golden, Colorado.

8. Bartone, Leonard M., Jr., "Alternative Power Systems for Extracting Energy from the Ocean: A Comparison of Three Concepts," Proceedings of the Fifth OTEC Conference (Miami, Florida, February 20-22, 1978), T. Nejat Veziroglu, Editor, University of Miami, 1978.

9. Beck, E. J., "Ocean Thermal Gradient Hydraulic Power Plant," Science, Vol. 189, 1975, pp. 293-294.

10. Beck, E. J., U.S. Patent 3,967,449, July 6, 1976.

11. Beck, E. J., "Nucleation of Steam Bubbles in a Proposed Ocean Thermal Gradient Hydraulic Power Plant," M-80-76-7, December 1976, U.S. Navy Civil Engineering Laboratory, Port Hueneme, California.

12. Zener, C. and Fetkovich, J., "Foam Solar Sea Power Plant," Science, Vol. 189, 1975, pp. 294-295.

13. Ridgway, Stuart L. and Charwat, Andrew F., "Scaled Experiments on Vertical Two-Phase Flow for Application to Mist-Flow OTEC Cycle," Proceedings of the Fifth OTEC Conference (Miami, Florida, February 20-22, 1978), T. Nejat Veziroglu, Editor, University of Miami, 1978.

14. Henrie, J. O., "Ocean Thermal Gradients – A Practical Source of Energy?" Science, Vol. 195, 1977, pp. 206-207.

15. Beck, Earl J., "Reply," Science, Vol. 195, 1977, p. 207.

16. Zener, Clarence and Fetkovich, John, "Reply," Science, Vol. 195, 1977, p. 207.

17. Fetkovich, J. G., Grannemann, G. N., Mahalingam, L. M., and Meier, D. L., "Studies of Biofouling in Ocean Thermal Energy Conversion Plant," Proceedings of the Fourth Conference on Ocean Thermal Energy Conversion (New Orleans, Louisiana, March 22-24, 1977), George E. Ioup, Editor, University of New Orleans, July 1977, pp. VII-15 to VII-25.

18. Kinelski, E. H., "Overview of Biofouling, Corrosion and Materials," Proceedings of the Fifth OTEC Conference (Miami, Florida, February 20-22, 1978), T. Nejat Veziroglu, Editor, University of Miami, 1978.

19. Henke, Thomas E., Hartt, William H., and Hart, Geoffrey K., "Evaluation of Selected Plastics for Application in OTEC Heat Exchangers," Proceedings of the Fifth OTEC Conference (Miami, Florida, February 20-22, 1978), T. Nejat Veziroglu, Editor, University of Miami, 1978.

20. Hafezzadah, Hafez, Johnson, D. W., and Starling, K. E., "Preliminary Analysis of Sea Water Leakage on the Performance of the Ammonia Cycle," Proceedings of the Fourth OTEC Conference (New Orleans, Louisiana, March 22-24, 1977), George E. Ioup, Editor, University of New Orleans, July 1977, pp. VIII-31 to VIII-36.

21. Trimble, Lloyd C., "OTEC Heat Exchanger Design and Producibility Study," LMSC-D507632, October 1976, Lockheed Corp., Sunnyvale, California.

22. Schreiber, C., "Ammonia Leakage in Seawater Experiment," Proceedings of the Fifth OTEC Conference (Miami, Florida, February 20-22, 1978), T. Nejat Veziroglu, Editor, University of Miami, 1978.

23. Dexter, S. C., "On the Localized Corrosion of Aluminum Alloys for OTEC Heat Exchangers," Proceedings of the OTEC Biofouling and Corrosion Symposium (Seattle, Washington, October 10-12, 1977), Battelle Pacific Northwest Laboratories, Richland, Washington, 1978.

24. Castelli, V. J., Fritsch, A. B., and Adamson, W. L., "An Evaluation of Some Mechanical Cleaning Methods for the Control of Microbiofouling in Heat Exchangers," Proceedings of the Fifth OTEC Conference (Miami, Florida, February 20-22, 1978), T. Nejat Veziroglu, Editor, University of Miami, 1978.

25. Fetkovich, John G., Grannemann, G. N., Mahalingam, L. M., and Meier, D. L., "Measurement and Mechanisms of Biofouling in OTEC Heat Exchangers," Proceedings of the Fifth OTEC Conference (Miami, Florida, February 20-22, 1978), T. Nejat Veziroglu, Editor, University of Miami, 1978.

26. Taylor, Barrie F., "Assessment of Microbial Fouling in an OTEC Study Near Saint Croix," Proceedings of the Fifth OTEC Conference (Miami, Florida, February 20-22, 1978), T. Nejat Veziroglu, Editor, University of Miami, 1978.

27. Craig, H. Lee, Jr., and Munier, Robert S. C., "Corrosion Results of Saint Croix Experiment," Proceedings of the Fifth OTEC Conference (Miami, Florida, February 20-22, 1978), T. Nejat Veziroglu, Editor, Universtiy of Miami, 1978.

28. Morse, J. W., deKanel, J., Van Valin, R., and Craig, H. L., Jr., "The Inorganic Chemistry of Aluminum Pipe Surfaces from the Saint Croix Biofouling and Corrosion Experiments," Proceedings of the Fifth OTEC Conference (Miami, Florida, February 20-22, 1978), T. Nejat Veziroglu, Editor, University of Miami, 1978.

29. Proceedings of the Ocean Thermal Energy Conversion Resource and Environmental Workshop (Cape Canaveral, Florida, June 27-28, 1977), W. R. McCluney and L. F. Lewis, co-editors, RD-77-2, Florida Solar Energy Center, Cape Canaveral, Florida, October 1977.

30. "OTEC Enivornmental Development Plan (EDP)," DOE/EDP-0006 (1977), March 1978, U.S. Department of Energy, Washington, D.C.

31. Karig, H. E., "Thermal Power Systems Using Ocean Temperature Gradients as Source of Energy," 72/WA/OCT-12, November 1972, The American Society of Mechanical Engineers, New York, New York.

32. "OTEC Power Plant Technical and Economic Feasibility," LMSC-D-056566, April 1975, Lockheed Corp., Sunnyvale, California.

33. Nath, John H., Amber, Julie W., and Hansen, Robert M., "Screens for the OTEC Plants." Proceedings of the Fourth OTEC Conference (New Orleans, Louisiana, March 22-24, 1977), Geroge E. Ioup, Editor, University of New Orleans, July 1977, pp. V-56 to V-69.

34. Thomas, David L. and Bason, William H. "Potential Use of Profile-Wire Screens for OTEC," Proceedings of the Fifth OTEC Conference (Miami, Florida, February 20-22, 1978), T. Nejat Veziroglu, Editor, University of Miami, 1978.

35. Little, Thomas E., "OTEC Seawater Pump Study," C00-4071-2, January 1978. Westinghouse Electric Corporation, Oceanic Division, Annapolis, Maryland.

36. Morello, A., "Bottom Power Cables Connecting Floating Power Stations to Shore," Proceedings of the Fifth OTEC Conference (Miami, Florida, February 20-22, 1978), T. Nejat Veziroglu, Editor, University of Miami, 1978.

37. Pieroni, C. A., Traut, R. T., Clark, B. S., and Smith, W. G., "OTEC Riser Cable: Problems and Costs," Proceedings of the Fifth OTEC Conference (Miami, Flordia, February 20-22, 1978), T. Nejat Veziroglu, Editor, University of Miami, 1978.

38. Curto, P. A., "An Update of OTEC Baseline Design Costs," Proceedings of the Fifth OTEC Conference (Miami, Florida, February 20-22, 1978), T. Nejat Veziroglu, Editor, University of Miami, 1978.

39. "Research on an Engineering Evaluation and Test Program," SAN-1089-TI-P1,2,3,4,5, June 1975, TRW Systems Group, Redondo Beach, California.

40. Lavi, Abrahim, "Solar Sea Power Plants, Cost and Economics," Proceedings of the Third OTEC Workshop (Houston, Texas, May 8-10, 1975), Gordon L. Dugger, Editor, Applied Physics Laboratory, The Johns Hopkins University, Laurel, Maryland, SR 75-2, August 1975, pp. 64-71.

41. "OTEC Power System Development. Phase 1: Conceptual Design," January 1978. Lockheed Corporation, Sunnyvale, California.

42. "OTEC Power System Development. Phase 1: Conceptual Design," May 1978, TRW Systems and Energy, Redondo Beach, California.

43. "OTEC Power System Development. Phase 1: Conceptual Design," January 1978, Westinghouse Electric Corporation, Lester, Pennsylvania.

44. "OTEC Platform Configuration and Integration," 1835-10 (N-10,000) – three volumes – June 1978, Gibbs & Cox. Inc., Washington, D.C.

45. "OTEC Platform Configuration and Integration," 5142-6. July 1978. M. Rosenblatt & Son. Inc.. New York, New York.

46. "OTEC Platform Configuration and Integration," July 1978. Lockheed Corporation. Sunnyvale. California.

47. George, J. F., Private communication of data from Abam Engineering regarding scale-up of results on the preliminary engineering design studies of a 20 MWe plant ship relevant to a 325 MWe commercial plant ship. January 1978. Applied Physics Laboratory, The Johns Hopkins University. Laurel, Maryland.

48. Eldridge, R. and Roberts, R., "OTEC Systems Descriptions and Engineering Costs." MTR-7485. Vol. VII, June 1977. The MITRE Corporation. McLean, Virginia.

49. Curto, P. A., "An Update of OTEC Baseline Design," Proceedings of Miami International Conference on Alternative Energy Sources. (Miami, Florida, December 5-7, 1977), T. N. Veziroglu, Editor, University of Miami. 1978.

50. Curto, P. A.. Private Communication Regarding OTEC Cost Estimates. 1978.

51. Lewis, Lloyd. Private Communication of a U.S. Department of Energy estimate, based upon Ocean Data Systems, Inc. OTEC thermal resource reports for Key West, Western and Central Gulf of Mexico (TID-27952, 27949 and 27951, respectively, of October 1977).

52. "OTEC Mission Analysis Study, Phase I," GE76TMP-67, November 1976, General Electric Tempo, Washington, D.C.

53. "OTEC Mission Analysis Study, Phase II," GE78TMP-64, March 1978, General Electric Tempo, Washington, D.C.

54. Trimble, Lloyd C., "OTEC Test Facilities Study Program," LMSC-D506781, January 1977, Lockheed Corporation, Sunnyvale, California.

55. Perry, A. M., Marland, G., and Zeiby, L. W., "Net Energy Analysis of an OTEC System," Proceedings of the Fifth OTEC Conference, (Miami, Florida, February 20-22, 1978), T. Nejat Veziroglu, Editor, University of Miami, 1978.

56. Homburg, C. D., Lindal, B., and El-Ramly, N., "Preliminary Research on Ocean Energy Industrial Complexes," ORO-4915-3, April 1976, DSS Engineers, Inc., Fort Lauderdale, Florida.

57. Avery, W. H., Blevins, R. W., Dugger, G. L., and Francis, E. J., "Maritime and Construction Aspects of Ocean Thermal Energy Conversion (OTEC) Plant Ships," SR 76-1B, April 1976, Applied Physics Laboratory, The Johns Hopkins University, Laurel, Maryland.

58. Francis, E. J., "Investment in Commercial Development of OTEC Plant-Ships," SR 77-3, December 1977, Applied Physics Laboratory, The Johns Hopkins University, Laurel, Maryland.

59. Konopka, Alex J., Talib, Abu, Yudow, Bernard, and Biederman, Nicholas, "An Optimization Study of OTEC Delivery Systems Based on Chemical-Energy Carriers," Project 8968, December 1976, Institute of Gas Technology, Chicago, Illinois.

60. Konopka, A., Talib, A., Yudow, B., Blazek, C., and Biederman, N., "Alternative Transmission Systems from OTEC Plants," Project 8980, DSE-2426-20, September 1977, Institute of Gas Technology, Chicago, Illinois.

61. Laurence, Scott and Roels, Oswald A., "Marine Pastures: A Byproduct of Large (100 Megawatt or Larger) Floating Ocean-Thermal Power Plants," (C00-2581-03, August 1976, Lamont-Doherty Geological Observatory, Columbia University, Palisades, New York.

62. Washom, Byron J., Nilles, Jack M., Lutz, Robert E., Nachtigal, Daniel, and Schmidhauser, John R., "Incentives for the Commercialization of OTEC Technology," Report to the National Science Foundation, January 1977, University of Southern California, Los Angeles, California.

63. Knight, H. Gary, Nyhart, J. D., and Stein, Robert E., OTEC Legal, Political, and Institutional Aspects (Published under the auspices of the American Society of International Law), Lexington Books, 1977.

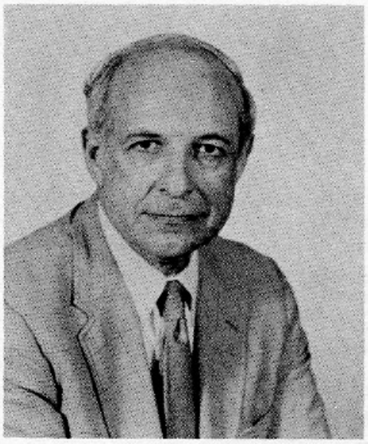
64. Ezra, Arthur, "Commercialization of OTEC," Proceedings of the Fifth OTEC Conference (Miami, Florida, February 20-22, 1978), T. Nejat Veziroglu, Editor, University of Miami, 1978.

65. Naef, Frederick E., "Economic aspects of OTEC," Proceedings of the Joint Conference of the American Section of the International Solar Energy Society (ISES) and the Solar Energy Society of Canada (Winnipeg, Manitoba, Canada, August 15-20, 1976), ISES, 1976.

66. Tefft, Clark, Kelly, Ratus Lee, Stevenson, Kathleen M., and Dick, C. Matthews, Jr., "Legal, Institutional and Financial Framework for OTEC Demonstration and Commercialization," Proceedings of the Fifth OTEC Conference (Miami, Florida, February 20-22, 1978), T. Nejat Veziroglu, Editor, University of Miami, 1978.

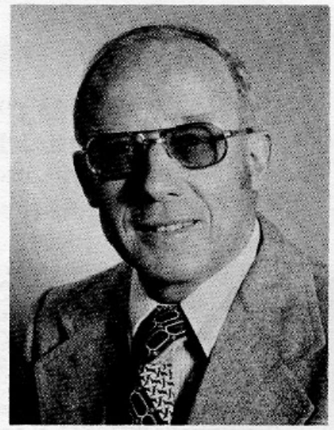
67. Lavi, Gay Heit, "An Approach to OTEC Commercialization," Proceedings of the Fifth OTEC Conference (Miami, Florida, February 20-22, 1978), T. Nejat Veziroglu, Editor, University of Miami, 1978.

MEET YOUR COE



BIOGRAPHICAL SKETCH: ROBERT COHEN

Robert Cohen is Program Manager, Oceans Systems Branch, Division of Central Solar Technology, U.S. Department of Energy, Washington, D.C. 20545. (Telephone: 202-376-4773). He was born in Indianapolis, Indiana. He served in the U.S. Navy in electronics from 1944–1946, including six months in China waters. He received the B.S. in Chemistry degree from Wayne University in 1947, and the M.S. degree (physics) from the University of Michigan in 1948. During the summers of 1948 and 1949 he was a physicist at the U.S. Navy Electronics Laboratory, San Diego, California. He received the Ph.D. degree (electrical engineering) from Cornell University in 1956. Subsequently, he was employed as a physicist at a laboratory of the National Bureau of Standards (NBS) in Boulder, Colorado. His group at NBS later became part of the Aeronomy Laboratory of the National Oceanic and Atmospheric Administration (NOAA) Environmental Research Laboratories. During the course of the work at NBS, he spent six years in South America performing ionospheric studies, mainly at the Jicamarca Radar Observatory, Lima, Peru. In 1973, he was assigned by NOAA to the Solar Energy Program of the National Science Foundation (NSF) in Washington, D.C.. That program was transferred to the Energy Research and Development Administration (ERDA) on 1975 January 19, and ERDA became part of the U.S. Department of Energy on 1977 October 01. At NSF, he was the original program manager for the Ocean Thermal Energy Conversion (OTEC) program.



Biography of THOMAS M. DAUPHINEE

Thomas M. (Tim) Dauphinee, born in July 1916 in Vancouver, B.C., Canada, met his wife Amy in 1939 when he was a penniless 23 year old school teacher in northern British Columbia near the starting point of the yet to be built Alaska Highway. With her help and encouragement he has since obtained three degrees, (all from the University of British Columbia). In the last (Ph.D) at age 34, he "found" physics and switched from teaching to full time research. In 1945 he joined the staff of the Physics Division of the National Research Council and except for a three year teaching and study break (1947–50) has been there ever since and is now Head of the Heat and Thermometry Section.

His contributions have ranged successively from solid state measurements (thermal and electrical conductivity, specific heat, Hall effect) to thermometry and precision electrical measurements (thermocouple comparisons, instrumentation for resistance thermometry) and more recently measurements in oceanography (in-situ and laboratory measurements of conductivity, salinity, temperature, pressure and plankton). In each of these fields he has achieved international recognition. Throughout his work has run the common thread of a deep interest in instrumentation and measurement which has led to a number of his designs being put into commercial production.

In addition, Tim has published over 40 technical papers and holds fifteen patents. He is a member of IEEE, ISA, CAP (Canadian Association of Physicists) and CMOS (Canadian Metrological and Oceanography Society). In the IEEE he is a member of the Council on Oceanic Engineering (Instrumentation and Measurement) and as Associate Editor of the Journal of Oceanic Engineering. He is also a scientific advisor to the UNESCO-SCOR WG 10 on Oceanographic Tables and Standards and a member of SCOR Working Group 51 on Evaluation of CTD data.

The 1978 Morris E. Leeds Award went to Tim "for the application of physical principles to electrical instrumentation and measurements."

BIOGRAPHY OF JOSEPH R. VADUS

Joseph R. Vadus, is a member-at-large on the IEEE Council on Oceanic Engineering. He has been an IEEE member for twenty-six (26) years and a senior member since 1958. He served as General Chairman for the combined MTS–IEEE OCEANS 76 Conference in Washington, DC during the Bicentennial year.

Mr. Vadus holds a B. S. degree in Electronic Engineering from Pennsylvania State University and a M.S. degree in Ocean Engineering from Long Island University, where he was an adjunct professor of Ocean Engineering for five years in the Evening Graduate Division. Mr. Vadus is presently Manager of Advanced Ocean Technology in the National Oceanic and Atmospheric Administrations (NOAA) Office Of Ocean Engineering and is responsible for research and development of ocean systems and equipment, the establishment of engineering standards and technology transfer. He is Program Manager for NOAA's ocean engineering activities associated with ocean energy, mainly Ocean Thermal Energy Conversion (OTEC). Previously, Mr. Vadus was Manager of Technology in NOAA's Manned Undersea Science and Technology (MUS&T) Office for four (4) years. Prior to joining NOAA, he was affiliated with Sperry Rand Corporation for twenty (20) years in management and senior engineering roles in research and development for advanced ocean systems, deep submergence vehicles, submarine instrumentation and control systems and radar and data processing systems. He has been awarded seven patents with three pending. He also conducted an Engineering Management course in the Sperry Rand Management Institute.

Several of his patents were incorporated in a three-dimensional tactical radar developed for the Marine Corps and used in the Vietnam War to provide most of the air traffic control over Vietnam. One patent provided automatic altitude on all aircraft under control.

His master's degree thesis on a radar system for deep submergence was built by Sperry and installed on the Navy's deep diving AGS-555 Dolphin Test Submarine. A patent on this design is pending.

In addition to his role in IEEE, Mr. Vadus is Vice President of the Marine Technology Society for Technical Activities. He is a member of the Society of Naval Architects and Marine Engineers (SNAME) and serves on their Submersibles Panel and Ocean Energy Panel, a member of the Society of Naval Engineers, and a member of the American Bureau of Shipping's Special Committee on Underwater systems and vehicles.