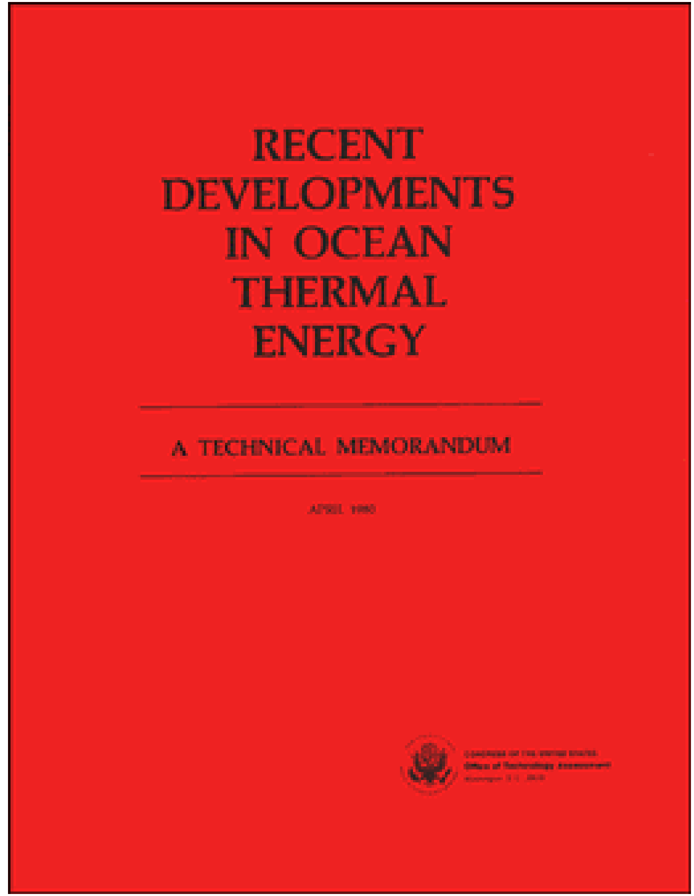
*Recent Developments in Ocean Thermal Energy*

April 1980

NTIS order #PB80-201825



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## PREFACE

This Technical Memorandum was prepared in response to a request from the Chairman of the Subcommittee on Energy Development and Applications of House Committee on Science and Technology. The Committee requested that the Office of Technology Assessment provide an update of its study of Ocean Thermal Energy Conversion (OTEC), which was published in May 1978.1

This Technical Memorandum reviews the status of OTEC technology developments as of April 1980. It discusses major technical accomplishments occurring after publication of the 1978 report and principal technical uncertainties that remain; it also attempts to summarize numerous documents and other available information in order to provide a concise update on the status of OTEC technology.

The Memorandum was developed over a two-month period by the OTA Oceans Program staff, with the assistance of Dr. Herman Sheets, a consultant who recently retired as the head of the Department of Ocean Engineering at the University of Rhode Island. In preparing the report recent DOE and industry reports were reviewed and there were consultations with those directly involved in recent technology development projects.

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# I. INTRODUCTION AND FINDINGS

OTEC is a proposed system for extracting useful energy from the solar heat stored in vast surface waters of tropical and semi-tropical oceans. OTEC systems aim to utilize the temperature difference between warm surface and cold, deep ocean water to power turbines and produce electricity. Some designs would use electricity for at-sea production of energy intensive products such as ammonia. The federal Department of Energy is sponsoring a major effort to develop the OTEC system as a future source of energy.

Much additional work has been done on OTEC since OTA's original report was issued. There have been a number of specific technical achievements and the funding level for the program has grown from about $15 million annually to a current annual spending pace of $40 million. Since the OTEC program was established in the Energy Research and Development Administration five years ago, the Federal government has invested over $100 million in it. In addition, a number of important technical projects have been privately funded.

The DOE is weighing data and awaiting results from additional tests before making a key decision on whether to support the first large pilot plant. Some critics of the DOE approach believe it is overly cautious and that enough information is now available to justify an immediate decision to build several pilot plants. Other critics feel that other energy technologies are more meritorious~

## MAJOR FINDINGS

The principal findings which can be summarized from this OTA analysis of current OTEC technology are:

1. The technology base for OTEC has improved over the past two years, and has consequently lowered the technical risk involved in constructing a moderate-sized (10-40 megawatt) pilot plant. It has not, however, developed to the point where the costs of large commercial plants can be accurately estimated.

2. The most significant technical accomplishments which have occurred over the past two years are the small scale (10 kilowatt) demonstration of system feasibility of Mini-OTEC (a barge-mounted test plant) and the improvements in several aspects of heat exchanger performance through laboratory and sea tests.

3. Very little has been done recently to evaluate the potential ocean thermal energy resources available for major OTEC commercialization; the present DOE development strategy does not adequately consider the future resource availability.

4. The OTEC program within DOE has grown in size and scope over the past two years and many competent technical groups have been involved in recent OTEC work. However, it is not certain that the project team could adequately respond to a major acceleration effort which would entail pilot plant construction prior to FY 82.

## 11. The OTEC Program

Within the DOE Office of Solar Technology, OTEC is one of five major systems development projects.[2] In 1978 when OTA published its OTEC assessment the DOE Program was just beginning to reach its present level of attention. The 1978 OTA report described the work leading up to this major Department of Energy program, and analyzed the status of the technology, the economic projections, and the government funding plans.

That report presented three options of future federal funding for consideration ranging from a no funding approach to a "systems development funding" approach which would entail annual costs of several hundreds of millions of dollars. The present Department of Energy program appears to be patterned after a middle-range approach which OTA described as an "R&D funding" approach.

Since 1978 much additional research work has been done on OTEC through this approach. A number of specific technical achievements have been recorded and **DOE program** funding has increased to almost $40 million annually; it is planned to remain at about that level through FY 81.

The past and future federal funding by major category is shown in a budget breakdown in Table 1. It can be seen from the budget breakdown that the DOE is switching emphasis from technology development to hardware testing. In fact, the OTEC-1 test platform which is scheduled to go to sea this June is currently using about one half of the program funds.[3]

Table 2 shows the DOE OTEC-1 schedule and the schedule for an OTEC Pilot Plant. DOE has assumed that enough information will be available by the beginning of FY 82 to make a decision on whether to proceed with a 10-40

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MW pilot plant. Such a plant would require a major increase in funding for construction, testing and evaluation.

DOE also has plans to fund studies of competing pilot power plant designs. Recent construction cost estimates for a 40MW pilot plant range between 150 and $300 million and the number of pilot plants which could or should be built is a matter of considerable debate. The proposed legislation which is now before Congress (S-1830 and HR 5796) suggests an accelerated program which would include construction of one or more plants to attain a goal of 100 megawatts by 1986 and 500 megawatts by 1989. The Congressional Budget Office estimates that such an accelerated program would cost $1 billion over the next five years.[4]

The DOE program strategy is to concentrate on the US island market potential for early OTEC pilot and demonstration plants but not to make a decision on the first or subsequent pilot plants until more test results are in. Bennett Miller of DOE, testifying before the House Science and Technology Committee in February 1980, stated that if results from OTEC-1 and other tests are encouraging and a decision is made to build an OTEC pilot plant, it is anticipated that detailed design and construction can be started in FY 1982 and completed in FY 1985. This pilot plant is planned to be of a scale sufficient to demonstrate the performance and reliability of both the total system as well as the individual components and to provide enough information for a decision to build a commercial size facility.[5,6]

While the strategy of building initial systems for island markets is considered logical by many, the pace of the program has been criticized by several of the private companies and researchers who have been involved in OTEC development over the past years. Some also claim that the plant ship

TABLE 1

OTEC Funding Summary
By Category
($ in Millions)

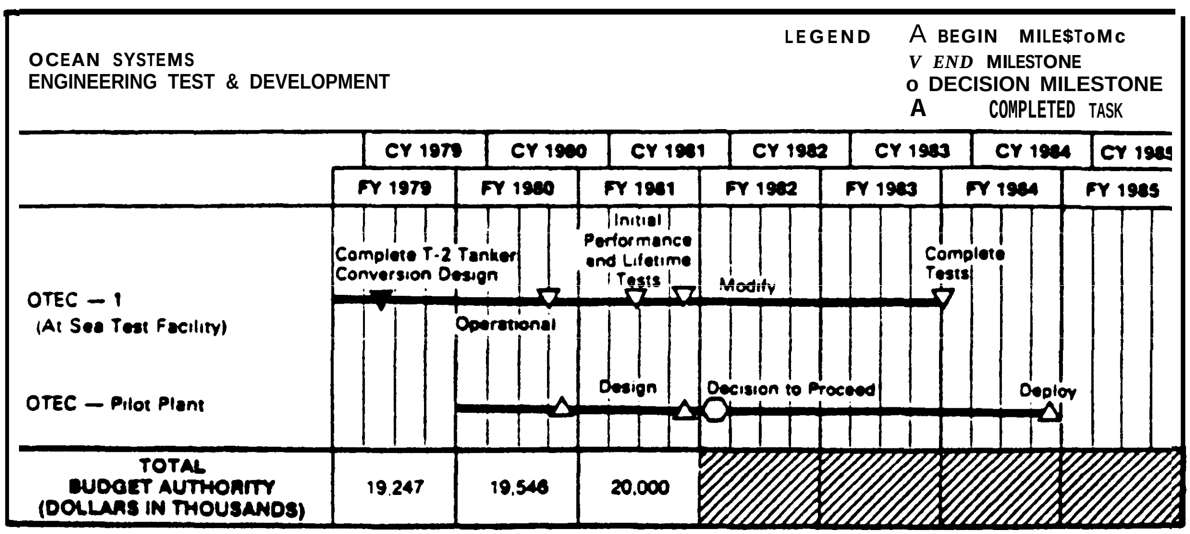
| Category | '75 | '76 | '77 | '78 | '79 | '80 | '81 | Total 7 Years |
|---|---|---|---|---|---|---|---|---|
| | Actual | | | | | Projected | | |
| Management | 0.1 | 2.1 | 2.1 | 2.5 | 3.7 | 4.7 | 4.5 | 19.7 |
| Planning | 1.6 | 2.7 | 1.2 | 1.6 | 3.0 | 3.0 | 2.9 | 16.0 |
| Advanced Research - | 1.2 | 3.5 | 4.5 | 5.0 | 1.0 | 1.0 | 1.0 | 17.2 |
| Technology Develop - | | 0.3 | 3.4 | 10.9 | 11.6 | 9.4 | 8.2 | 43.8 |
| Mostly Testing (OTEC-1) - | | | 3.3 | 9.0 | 19.2 | 19.5 | 20.0 | 71.0 |
| Total | 2.9 | 8.6 | 14.5 | 29.0 | 38.5 | 37.6 | 36.6 | 167.7 |
| Cum. Total | 2.9 | 11.5 | 26.0 | 55.0 | 93.5 | 31.1 | 67.7 | |

(Fiscal Year)

Source: U.S. Department of Energy, Ocean Energy Systems Program Summaries for FY 77, 78 and 79 and Solar Energy Program Summary Document for FY 81.

TABLE 2

Milestones and funding of OTEC Testing Program -




Source: U. S. Department of Energy, Solar Energy Program Summary Document FY 1981.

option to develop an OTEC system which could be located in the tropical oceans to produce ammonia or other energy intensive products has not been adequately considered in the strategy.[7]

Whether the program could or should be accelerated and what the appropriate level of government involvement might be are the subjects addressed by pending legislation. The pending legislation includes two types of bills both of which have been introduced in the House and Senate. The first type (S 1830 and HR 5796) requires the Department of Energy to prepare a comprehensive plan leading to OTEC commercialization demonstration goals. The second type (HR 6154 and S 2492) provides a licensing system for OTEC and financial incentives for commercial and demonstration facilities. The technical risks involved in a decision to accelerate the program are described in section IV of this paper. It appears, however, that whether a pilot plant is built next year or the year after will be determined more by policy direction and management capability of the Department of Energy than by technical considerations.[8]

The OTA review of past DOE funding and development work indicates that the number of focused technical accomplishments is modest compared to the money spent. However, the work has helped to build an institutional capacity consisting of a number of experienced technical groups. The DOE staff is located in several field offices as well as in Washington headquarters. Several systems contractors also provide management support to each of the DOE offices. The groups now involved in OTEC work are large and diversified, include many competent technicians and some major private companies with relevant experience. They are also spread over many locations which makes it difficult to coordinate the diverse pieces of work.

In their multiyear program plan, DOE has projected that, even with an accelerated effort, large budget additions would not be needed before FY 82.

Given the present DOE management system, it does not appear likely that OTEC pilot plant construction could be initiated much earlier than the FY 82 date now planned.

## 111. The Ocean Resource

OTEC plants make use of the differential temperature between the surface and deep ocean water masses. Thus, potential energy resources are greatest in tropical regions of the ocean where surface temperatures remain warm (about 80°F) throughout the year, and where cold water is available at reasonable depths.

OTA's 1978 report noted that no one had undertaken total assessment of the ocean's thermal resources and their relationship to the amount and kind of energy needed in specific locations. It did not appear that a commercialization strategy for OTEC could be developed without, having more detailed information and analysis of the potential thermal energy resource. Since that report, it does not appear that DOE has completed even a preliminary assessment of this kind which could be used in their own planning and commercialization of OTEC power systems. [9]

It has been estimated that over 20 million square miles of suitable ocean area exists worldwide for OTEC sites [10]. The DOE estimates the upper extractable limit of this renewable resource as 200 quads ($10^{15}$ Btu) per year. (One quad per year of electrical output is roughly equivalent to 11,000 megawatts operating 100% of the time) The magnitude of the thermal resource available to the United States for exploitation has been estimated by DOE to be tens of quads per year. These resource numbers have not been documented by DOE; it has not identified the sites for each estimate; and it has not stated the assumptions used in making these estimates.[11]

### Island and Gulf Coast Resources

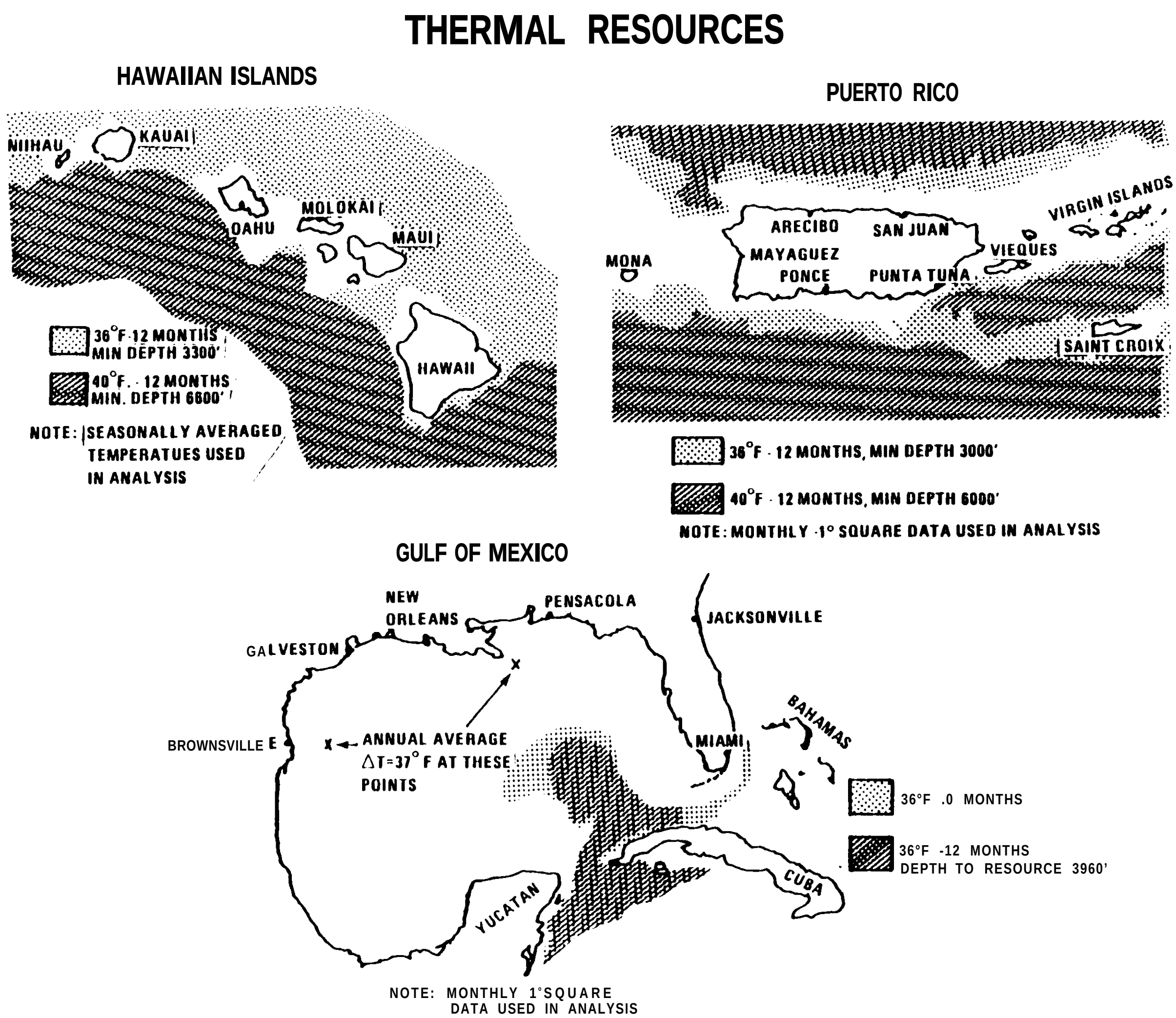
Resource development strategy has also not been defined in existing DOE planning documents. The DOE "island strategy" for electrical power generation has targeted the U.S. island market as ideal for OTEC development. OTA recommended in the 1978 report that it would be beneficial to emphasize such specific development of island sites in the Caribbean and Pacific Oceans.

DOE has projected incremental baseload electricity needs of U.S. islands and the Gulf Coast. OTEC seems well-suited to the U.S. island market because the cost of alternative incremental generation capacity is so high for islands. The DOE strategy for commercialization also depends heavily on penetration into the much larger continental U.S. electricity demand in the Sunbelt region adjacent to the Gulf of Mexico. In this market, OTEC plants must compete with baseload fossil and nuclear generating plants.

Even though DOE future projections appear to rely heavily on developing OTEC sites in the Gulf of Mexico, this has not been based on a detailed analysis of the total resource that would be available to the U.S. Some researchers have developed dynamic models of the ocean temperature in the Gulf but these have yet to be verified. OTA made a very rough estimate of total potential OTEC electrical production from the Gulf of Mexico in its 1978 report and concluded that about 15,000 megawatts may be available for U.S. markets. While this estimate has also not been verified, it does indicate that there may be some limits on resources in this particular region.[12, 13]

Another question to be addressed in analyzing the Gulf of Mexico resource is that of U.S. jurisdiction. Most of the resource now identified is outside of 200 miles from U.S. shores and inside 200 miles from Cuban and

Figure 1




THERMAL RESOURCE AVAILABILITY FOR THE HAWAIIAN ISLANDS, PUERTO RICO, AND THE GULF OF MEXICO

Source : U.S. Department of Energy, Draft Multiyear Program Plan, Ocean Systems, Oct., 1979.

Mexican coastlines. This is now considered international waters but it is by no means easily accessible to large U.S. electrical markets.

Plant Ship Resources

The OTEC plant ship concept uses the electricity generated from the thermal temperature differences to produce an energy intensive product such as ammonia. This concept avoids the requirement of the electric cable from the OTEC plant site to the user. Instead, a product will be shipped by barge or by pipeline to the end user.

To gain maximum OTEC efficiency, there is an incentive for the plant ship to be located where maximum temperature differences exist between the surface and deep ocean water. These locations may be in the tropical Atlantic or Pacific or even in the large ocean regions near the long Hawaiian Island chain, all of these both regions having very large resource potential. Thus, the plant ship may be located in international waters, a considerable distance from the product markets of the continental United States.

Summary

The Department of Energy has projected that OTEC will be able to serve major U.S. markets through the use of Gulf of Mexico sited electrical generating systems and plant ships in the tropical oceans. They have projected 50,000 megawatts for the Gulf of Mexico and Plant ships by the year 2010. It is not stated, however, what portion of this number would be electrical generation or plant ships. Since the types of systems are very different and since there is a huge difference in possible resources between Gulf of Mexico and the tropical oceans, a strategy for resource evaluation is urgently needed. More attention should also be given to careful analysis of all feasible ocean thermal resources that will have an effect on OTEC development.

## IV. The Technology Base

The technology base for OTEC has **improved over the past two years. Substantial and significant** work has been accomplished.

The OTA report in 1978 detailed the history and background of the development of the OTEC concept. As stated in 1978, no technological or scientific breakthroughs are needed for OTEC to become a commercial reality. However, there are still formidable engineering development challenges in getting from the present state of development to many, large economically competitive commercially operating systems.

Two basic uses have been proposed: baseload electrical generation and the power supply for manufacture of an energy-intensive product such as ammonia. These have been the most thoroughly examined of the potential OTEC uses. There are conceptual designs of systems for both applications which have changed only slightly since 1978*

Regardless of the design and end use, each OTEC would require an ocean platform, a heat exchanger and a cold water pipe. If the system were to provide electricity to a busbar, it would require underwater transmission lines and a mooring system. An OTEC used to produce a product such as ammonia would probably have a propulsion system enabling it to move from site to site, thus capitalizing on areas where the greatest differences of temperature exist between water at the surface and at the cold water pipe inlet. A large commercial system would be of about 400 megawatt capacity. The present **program** is directed primarily at developing the technology which could be incorporated into future possible commercial systems.

Within a logical technology development process, the construction and operation of a pilot plant would be very desirable to fully test a total system design under seagoing conditions. Only after a pilot plant test program is well underway can any accurate estimates of long term commercial economic and technical feasibility be established. Unfortunately for such systems as OTEC, even a pilot plant program is likely to be very costly.

OTEC technology has been developed to the stage where a moderately sized (10-40 MW) pilot plant can probably be designed and constructed. The most significant technical risks are in the areas of cold water pipes, heat exchangers and electrical transmission cables. These three areas probably need component tests and evaluations prior to building a complete system for a pilot plant. OTEC-1 will be a floating test platform intended to evaluate heat exchangers of one megawatt* size. Other component tests are also planned.

OTEC development work has shown substantial progress during the last two years. A significant event was the operation of Mini-OTEC during the summer of 1979 in Hawaii, showing that a small OTEC system can generate net electrical output. The progress in fouling countermeasures and the development of heat exchangers with overall heat transfer coefficients of about 1000 are also note-worthy.** As a result, there is now more confidence in the prediction of OTEC technical performance.

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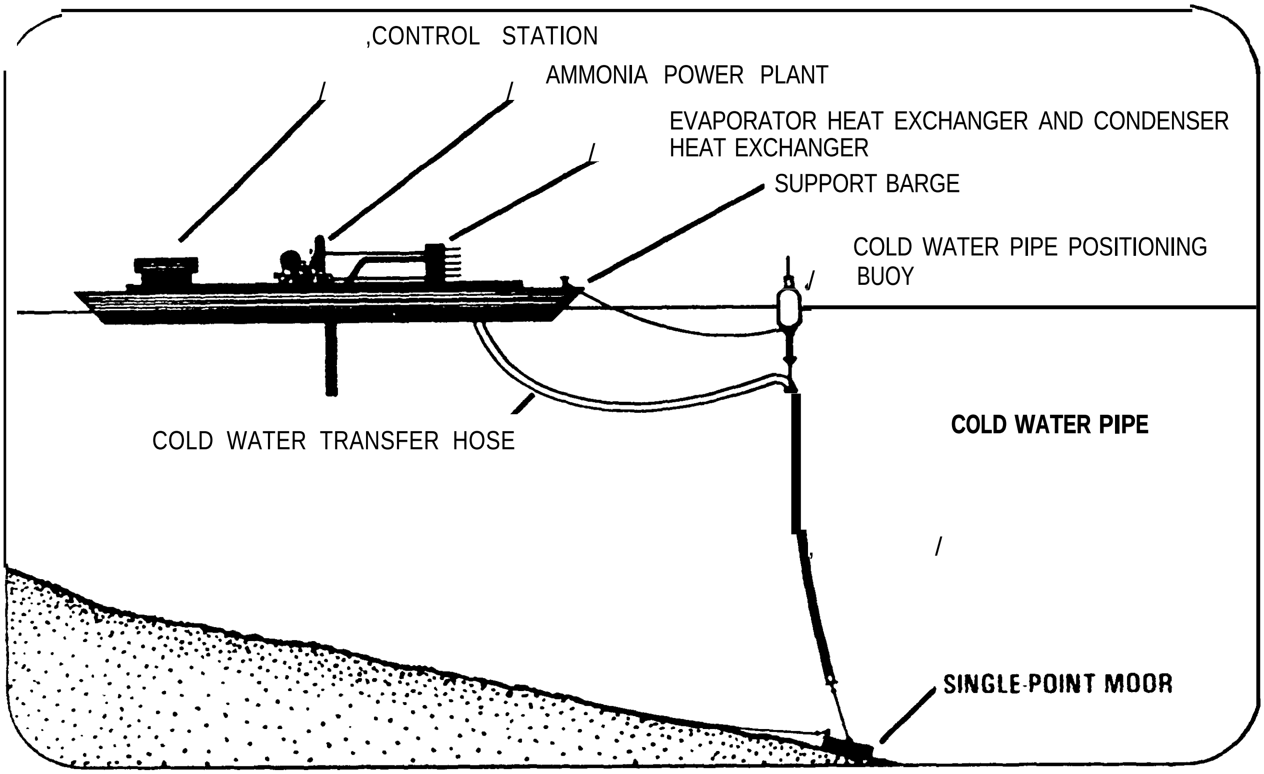
* Plant electrical output.

** Large heat exchangers in standard electrical power plants usually operate with heat transfer coefficients of less than 400.

**Figure 2**

**Schematic of Mini-OTEC**

**A Small Scale System Concept Test Bed
Which Operated off Hawaii During Aug.-Oct. , 1979**




Source: Lockheed Missiles and Space Co.

The following sections describe the status of the major technological developments which make up a complete OTEC system.

## Significant Accomplishments

Significant accomplishments in the OTEC program have been the operation of Mini-OTEC and technical progress in understanding fouling and keeping heat exchanger surfaces clean.

## Mini-OTEC

The Mini-OTEC program was a joint venture costing about $2.5 million between the State of Hawaii, Dillingham Corporation, and the Lockheed Missile and Space Company with the U.S. Navy furnishing the barge for the program. Mini-OTEC's purpose was to generate net power according to the temperature difference between the warm and cold water resource. This was considered by many to be and the proof of principle for an OTEC system. The cold water pipe was fabricated of 24-inch diameter polyethylene in a length of 2150 feet. It started operation in August 1979, and ran for a period of about 2 months. During this time, the Mini-OTEC plant operated for 2 weeks continuously and met its design goal of 50 to 55 kilowatt gross electrical power with 10 to 12 kilowatt net electrical power output. The 40 kilowatt difference was used to power pumps and other auxiliaries. Heat exchangers were fabricated of titanium and were of the plate type design. Although this was essentially a private venture, it benefitted from a combination of technology developed under government sponsorship and off-the-shelf commercial hardware.[14]

## Progress in Understanding Bio-Fouling

Another accomplishment in the OTEC program during the last three years was progress in the field of micro-fouling (slime formation on heat exchanger elements). The OTEC program has recognized the importance of bio-fouling, corrosion, and the selection of materials for establishing the feasibility of the entire OTEC system. It was recognized early that the selection of materials would significantly affect cost and performance of the entire OTEC system.

As a result of the work done during the last two years, considerably more knowledge is available regarding micro-fouling and its accumulation for the design of heat exchangers for long-range operation and high performance. Information is available on a variety of cleaning methods for both the mechanical and chemical systems. In addition, ultrasonic cleaning methods are being investigated. Consequently, it appears that for some designs micro-fouling can be overcome by appropriate countermeasures.[15]

## Status of OTEC Component Development

### Platforms

Of the various **OTEC** components, the platform represents relatively few technological problems. The platform for a 100-400 MW commercial OTEC power plant is approximately the **same size** as very large oil drilling platforms. The building material can be reinforced concrete or steel; such platforms have been built in a number of industrial countries. Thus, the size and design of the platform does not represent new concepts or technology. However, long-life and survivability represent factors which require additional attention. The station-keeping and mooring will require specific data and designs for a site. A system for mooring large commercial plants in **deep water is beyond the state-of-the-art and engineering development may** be required. Numerous engineering studies of platforms and moorings have been completed over the past few years; however, except for Mini-OTEC and OTEC-1 testbeds, none have been constructed.[16]

Cold Water Pipe

The fabrication, deployment, and connection of the cold water pipe to the platform will require a substantial engineering effort. For the Mini-OTEC plant, the 24 inch polyethylene cold water pipe performed satisfactorily. It can also be expected that for OTEC pilot plants, in the 10 to 40 megawatt range, the cold water pipe may not be a insurmountable problem. However, for large plants (400 MW) where the cold water pipe can be approximately 100 feet in diameter and up to 3000 feet long, it will be considerably more difficult to design and build a pipe which can be subjected to movements in all three axial directions and in rotation about several axes. A substantial amount of work is presently being undertaken for cold water pipe design and analysis. Several configurations and materials have been proposed as feasible candidates. However, long lifetime requirements and survivability are presenting uncertainties for the large pipes. Dynamic loadings on the pipe due to wave action and stresses due to platform motions are recognized as problems affecting pipe design. At this time, rigid materials such as reinforced concrete and steel are being analyzed together with more compliant materials such as a variety of plastics with reinforcements and possibly nylon-reinforced rubber. It is also quite possible that the design of the cold water pipe will be location-dependent, similar to the cooling water discharge pipes from the condensers of existing central station power plants. Considerable physical oceanographic data will be required to optimize the location of the OTEC plant to determine the best cold water pipe design. once a successful design for the cold water pipe has been established, there will be a need for production engineering and the establishment of manufacturing facilities for the cold water pipe. Pipe materials will be an important consideration and their selection may be affected by size and volume. Advanced handling procedures will be needed for the large cold water pipes. It will be important to undertake ocean testing of the cold water pipe. 17, 18

Heat Exchanger

**The heat exchanger for the closed cycle OTEC plant represents the most important component because of its size, weight, and cost. A** variety of designs have been proposed and tested. Some of these units are of the shell and tube type with the sea water inside the tubes and the evaporating ammonia on the shell side. Various types of heat transfer enhancement techniques, such as flutes to promote local turbulence, have been analyzed and tested on both the water and ammonia sides of tubular heat exchangers. Plate heat exchangers have also been tested with ammonia side enhancement. As a result of the many analytical and experimental data which have been accumulated during the last two years, substantial progress has been made. An OTEC heat exchanger with a total heat transfer coefficient of about 1000 can be expected in a modern heat exchanger design. This type of design would have no system to enhance heat transfer on the water side so that it can be easily cleaned for fouling purposes. This total heat transfer coefficient is about two to three times the value attainable two or three years ago. If the heat exchanger has no enhancement on the waterside there is no increase in pumping power. It can be expected that the same high heat transfer coefficient will be achieved with the plate and fin type heat exchanger, The experimental confirmation of the high heat transfer coefficient performance is a significant advancement in heat exchanger technology. If a chemical fouling countermeasure is used, then additional enhancement on the waterside can be used, possibly further increasing the overall heat transfer coefficient.

At this time, titanium promises the greatest reliability for an OTEC heat exchanger. Stainless steel and aluminum offer opportunities for less expensive heat exchanger materials and also result in lower fabrication cost. However, additional studies and experimentation are needed for these materials to guarantee the same reliability and long life as titanium when subjected to the anti-fouling countermeasures.[19, 20]

Other working fluids besides ammonia have been suggested. These include various combinations of hydrocarbons and freons. For these fluids copper-nickel could be used in the heat exchanger and thus the problems of fouling and corrosion would be substantially reduced. Some basic work on additional fluids may be justified so that large potential changes in performance are not overlooked. Plastic heat exchangers have been suggested. Such units may offer the potential of lower cost. However it may take several years for these new materials to meet all the tests for endurance. overall, considerable progress has been made in heat exchanger design and performance. Its technical performance can now be estimated with greater confidence than before. Long-range development of a lower cost heat exchanger material will be desirable. Additional tests to optimize cleaning methods will be needed to minimize the cost of cleaning while meeting performance and environmental requirements.

Power System Components

The power turbine is a component which has received only limited attention. This appears justified in view of such major problems as heat exchanger design and fouling. However, the power turbine with ammonia as a working fluid in the sizes contemplated for a commercial plant has never been built. Since the heat of evaporation for ammonia and the enthalpy drop through the turbine are considerably less than those of existing steam power turbines, there may be a need to study turbine stability as well as turbine control. In addition, it may be desirable to study the effects of ammonia leaks on the entire power plant system.

Pumps may require special attention because they will deliver large amounts of salt water against a relatively low head. It has been proposed to have two or more of these pumps operating in parallel. Such high specific speed pumps may be difficult to operate satisfactorily in parallel unless they are provided with a special control system. The pumps and their power requirements critically affect a total power demand to start the OTEC plant. Considerable attention must be given to the starting requirements of the OTEC plant and the associated power supply.

A number of alternative power cycles have been investigated. They include the open cycle, hybrid cycle, the foam cycle, and the mist cycle. The open cycle has some merits for small units and its ability to supply fresh water and should be pursued. However, substantial support of the other cycles appears no longer justified because after considerable length of study their technical and economic success is very much in doubt. Some other innovative power cycles may be pursued as long-range research projects until their technical feasibility and potential economic benefits are credibly evaluated. The problem of such long-range R&D) is the lack of a central evaluation authority. There could be benefits to investigating cycles which require smaller amounts of cold water per megawatt of electricity or systems which will reduce fouling.[21, 22, 23]

Electrical Power Transmission Cables

Prior studies by the Office of Technology Assessment on the OTEC Program pointed out the state of art of underwater electrical power transmission citing examples of technology used in Norwegian waters. These commercial developments have not extended that technology to what is required for OTEC; nor is it expected that a commercial need will arise for such extended technological development separate from OTEC.

The analysis of potential power cable failure modes have been undertaken by the Simplex Wire and Cable Company as well as Pirelli Cable Systems, Inc. both of which have considerable experience in the design and fabrication of underseas cables. Several designs have been prepared for overcoming the severe problems associated with the riser cables and two prototype cables incorporating different insulation techniques are being manufactured for ultimate application to the 10-40 MW pilot plant. Three cables of about 6 inches diameter each will be required. The prototypes have to undergo extensive testing and if failures occur, will have to be redesigned and recycled through testing. The whole process of design, testing, redesign, retesting, preparation of manufacturing specifications, manufacturing engineering, and further laboratory and field testing of the cables to assure long life will take a minimum of 3 to 4 years. Plant modifications for full cable length manufacturing and the associated detail manufacturing engineering can then proceed followed by the actual fabrication for a 100-400 MW OTEC. Manufacturing samples of the early cable runs may well have to undergo further tests.

**Thus** a major development effort will be required to provide highly reliable underwater power transmission cables to connect 100-400 MW offshore OTEC power plants to onshore consumers. Technologically , this cable must be considered as two distinct parts: the ocean floor cable that runs from shore to the OTEC site and the riser cable that connects the OTEC plant to the ocean floor cable. The ocean floor portion will require fewer technological advances as compared to the riser cable. Deeper depth operating capability than present experience (1000 m to 1500 **m** as compared to 550 m) will probably be achieved for the ocean floor cable without major difficulty.

The technological advances required however for developing a long life riser cable are considered to be significant. The riser cable will be subject to continual accelerations induced by the platform motion in response to the sea as well as its own response to ocean conditions. These accelerations, pressures differentials, and specific weight and other physical differences of the various elements of the riser can result in early failure of the insulation. The development of reliable splicing techniques for connecting the riser to the ocean floor cable and for repairs will also require development and extensive life testing. A further complexity will be introduced for transmission lines that are over 50 miles long (most Gulf of Mexico sites fall within this category). These transmission lines will probably have to be designed for very high voltage DC rather **than AC to minimize power losses. This will affect the selection of insulations as well as the internal cable construction. In view of the** foregoing, it will be necessary that the cable design take into account system aspects such as expected sea conditions, Platform movement and cable laying techniques and capability, as well as the techniques of attachment of the riser cable to the platform. Concepts of integration of the riser cable with the platform cold water pipe will have to be weighed against repairability , maintenance requirements, and technological trade-offs.

If several OTEC plants are to be installed within the next decade there may not be enough cable manufacturing facilities in the United States or possibly in the world to provide enough cables for the OTEC programs. New cable manufacturing facilities in a coastal area may be needed together with the requirements for cable laying ships or barges. With modern engineering methods it may be possible to substantially reduce the cost of cable manufacturing and cable laying.[24, 25, 26, 27]

OTEC-1

The OTEC-1 floating test facility will begin at-sea operations in June of this year. Converted from a Navy type T-2 tanker by Global Marine Development, Inc., it is a test facility designed to evaluate heat exchanger components. OTEC-1 includes a cold water pipe, pumps, and an ammonia evaporation/condensation loop. The cold water pipe consists of a bundle of three 48 inch diameter polyethylene pipes each 2100 feet long with a steel cable running through to a weight on the bottom.

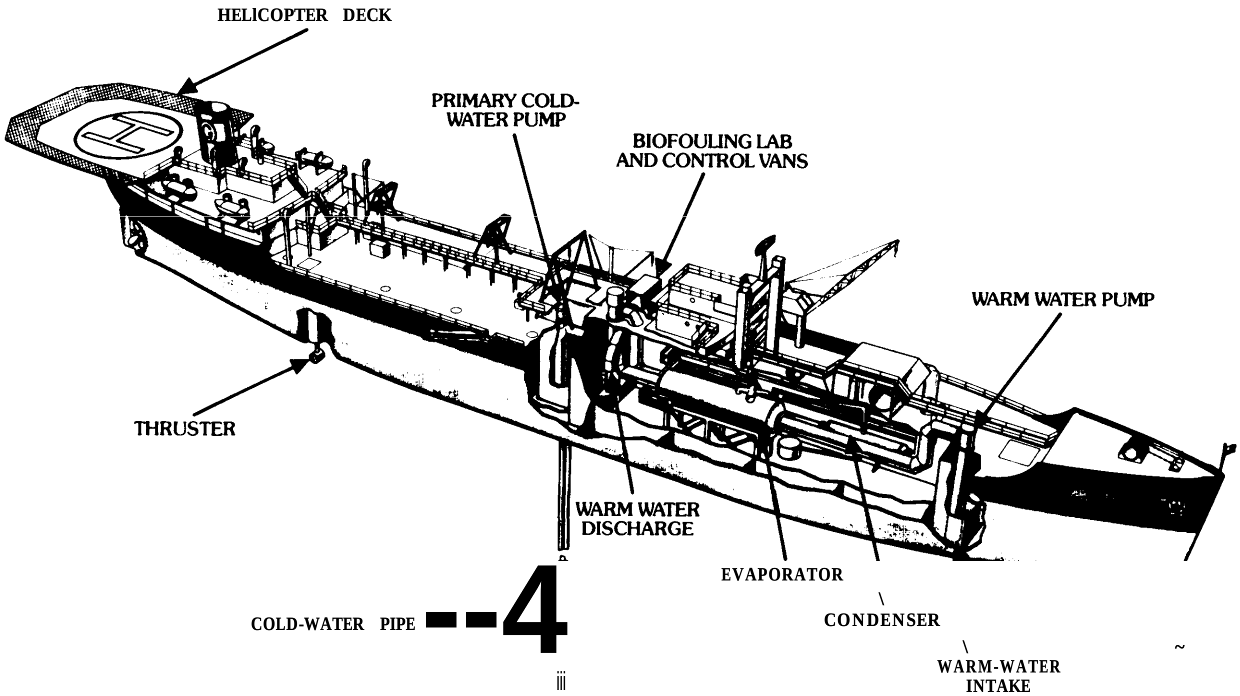
The first heat exchangers to be tested on OTEC-1 are one megawatt, conventional titanium shell-and-tube designs for evaporation and for condensing furnished by TRW under contract to DOE. Each is about 50 feet long by 10 feet in diameter and contains 6,000 tubes. Following 8-9 months allocated to tests on this design, it is planned that the ship will be returned to port, the heat exchangers removed, and up to four smaller 0.2 megawatt units of advanced design installed for tests.[28]

The actual expenditures for the design and conversion of OTEC 1 are now projected to be about $7 million more than the original budgeted amount of $33 million. This was caused by a number of factors including difficulties encountered after the mothballed tanker was carefully inspected to see which systems needed replacement. Such an overun is not unusual in large engineering development projects and it might be expected that future overuns could occur when the much more difficult OTEC technology development and testing work is undertaken.

To what extent the results of OTEC-1 tests are necessary for the design and construction of a pilot plant is a matter of considerable debate. At present, it is not possible to determine because **DOE has not** defined which pilot plant concept or strategy they wish to pursue. If a concept for a pilot plant had been selected, a logical program of component testing aboard a test platform could be developed. For some pilot plant concepts OTEC-1 may have limited usefulness. For others, component testing could include heat exchangers, cleaning methods, parts of cold water pipes and electrical riser cables. It now appears that only one type of heat exchanger, which may or may not be suitable for a pilot plant, will be tested on OTEC-1 prior to FY 82.

It is **too early to report any accomplishments** ***from*** the OTEC-1 test platform but it appears that most of the hardware has been built on schedule and by 1981 some initial at-sea heat exchanger test results should be available.

Figure 3




**OTEC-1 FLOATING TEST PLATFORM being designed and built Global Marine Development, Inc. and TRW is a converted Navy tanker. It will be used to evaluate different (OTEC components and operation of the heat exchange loop, including cold water pipe and ammonia evaporation, condensation, and recirculation. TRW designed the heat exchanger under a separate contract with the Department of Energy. The ship will be anchored off Ke-ahole Point near the island of Hawaii.**

Source: Quest, New Technology at TRW Defense and Space Systems Group, Autumn, 1979.

Pilot Plant Design for an OTEC Powered Ammonia Plant

A **conceptual integrated design of a 40 megawatt pilot plant** has been completed under contract to DOE by the Applied Physics Laboratory of Johns Hopkins University using the APL plant ship concept. This design calls for a concrete platform approximately 450 feet long of almost 100,000 tons displacement. It's four modules would generate 10 megawatts each. A lightweight concrete cold water pipe 30 feet in diameter and 3,000 feet long with four cold water pumps is proposed. The design can be either a moored plant with an electrical cable to shore or a grazing plant and include an ammonia conversion plant. The Johns Hopkins Applied Physics Lab is now completing a report on this design which includes a complete system concept design. Heat transfer tests of some laboratory conducted ultra-sonic cleaning tests of the heat exchanger indicates promising results. A section of the cold water pipe is being fabricated for test. APL has estimated the cost of a 40 MW pilot plant with no profit or contingencies to be $140 - $160 million.[29]

Ammonia Conversion/Fuel Cells

**The prospect for developing an OTEC system for operating in the tropical coceans has led to design studies of ammonia conversion systems** for **these plants and of fuel cells which may be powered by ammonia produced by these plants.**

**APL's** first **OTEC Plant Ship concept used the solid polymer electrode (SPE) electrolysis system to produce hydrogen from seawater. The cells use electricity to manufacture hydrogen at voltages of** 1.6 to 1.9 volts (direct current).[30]

Figure 4

**Baseline pilot>**

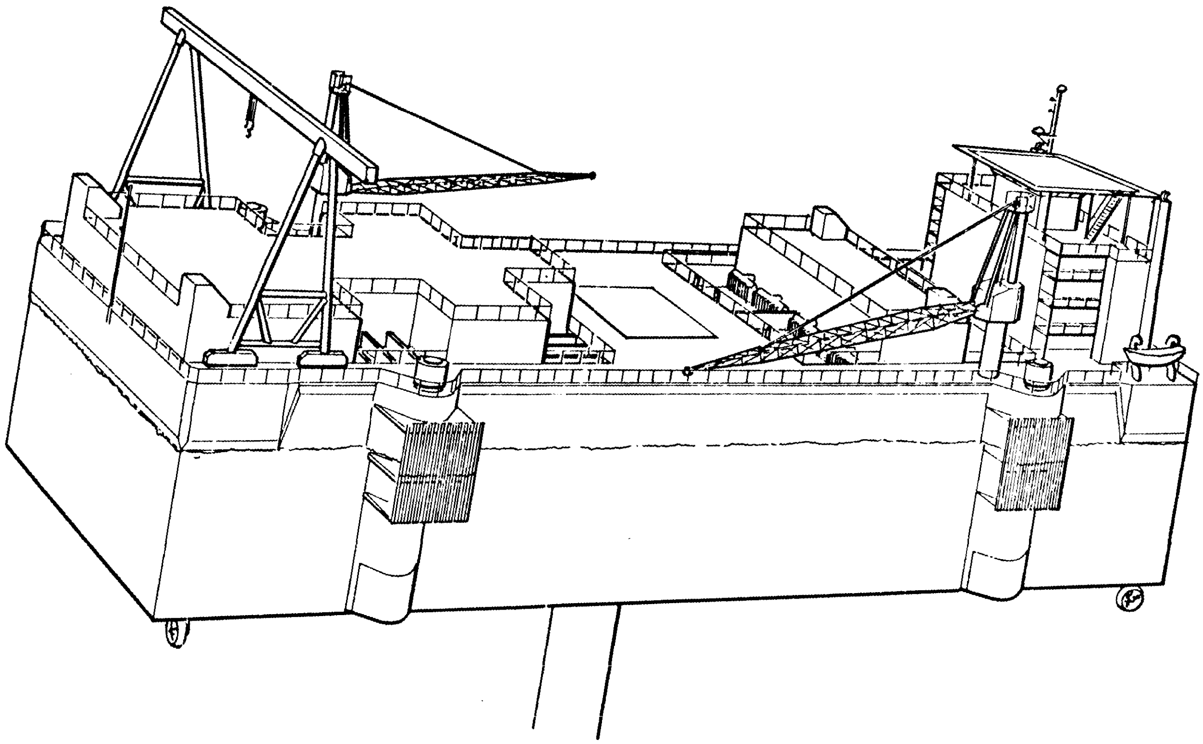
Proposed by

*by Johns H ‘‘~ant Concept Design*

*40 ~ E l ectrfcal m -‘p 125 Ap. STPDed Amm physics ‘ab*

30 ‘t” Diameter Light Concrete Cold Water Pipe

Concrete Hull onia



Source: Johns Hopkins Applied Physics Lab.

Currently, General Electric has a 50 KW unit for generating electricity from hydrogen operating in the laboratory. The electrodes on these cells are made of platinum and blends of other noble metals. They have in some instances operated over 20,000 hours with negligible deterioration. GE is working on ways to reduce the noble metal content of the cell electrodes.[31]

Avery has published a paper including cost estimates for an ammonia-OTEC fuel cell cycle using SPE cells. The paper claims a 50-55% efficiency of the SPE fuel cell cycle using present systems going up to 60 to 65% achievable at low current densities with further R&D effort. While such systems may be possible in the future, considerable R&D effort will be needed.[32]

Sea Solar Power-Plant Designs

A somewhat different approach to OTEC plant design has been suggested by Sea Solar Power, Inc. of York, Pennsylvania. They have concentrated R&D attention on a system using a halocarbon instead of ammonia as a working fluid and incorporating their patented high performance heat exchanger. They have built and tested a small working model and have prepared a conceptual design for a 100 megawatt plant. Much of their work has been funded internally. Some of their concepts deserve development attention in future OTEC designs because breakthroughs in heat exchangers could be the most significant factor for future economic viability.[33]

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