Proc. MTS '90 Conf.
Washington, D.C.
(Sept. 26-28, 1990)

CONF-9009249--1
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CONF-9009249--1

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OCEAN THERMAL ENERGY CONVERSION -- PERSPECTIVE AND STATUS*

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ABSTRACT

The use of the thermal gradient between the warm surface waters and the deep cold waters of tropical oceans was first proposed by J.A. d'Arsonval in 1881 and tried by George Claude in 1930. Interest in OTEC and other renewable energy sources revived in the 1970s as a result of oil embargoes. At that time, the emphasis was on large floating plants miles from shore producing 250-400 MW for mainland grids. When the problems of such plants became better understood and the price of oil reversed its upward trend, the emphasis shifted to smaller (10 MW) shore-based plants on tropical islands. Such plants would be especially attractive if they produce fresh water as a by-product.

During the past 15 years, major progress has been made in converting OTEC unknowns into knowns. Mini-OTEC proved the closed-cycle concept. Cost-effective heat-exchanger concepts were identified. An effective biofouling-control technique was discovered. Aluminum was determined to be promising for OTEC heat exchangers. Heat-transfer augmentation techniques were identified, which promised a reduction on heat-exchanger size and cost. Fresh water was produced by an OTEC open-cycle flash evaporator, using the heat energy in the seawater itself. The current R&D emphasis is on the design and construction of a test facility to demonstrate the technical feasibility of the open-cycle process.

The 10 MW shore-based, closed-cycle plant can be built with today's technology; with the incorporation of a flash evaporator, it will produce fresh water as well as electrical power -- both valuable commodities on many tropical islands. The open-cycle process has unknowns that require solution before the technical feasibility can be demonstrated. The economic viability of either cycle depends on reducing the capital costs of OTEC plants and on future trends in the costs of conventional energy sources.

INTRODUCTION

The concept of producing power from the thermal gradient in the tropical oceans has been around since 1881, when the French scientist, J.A. d'Arsonval, first proposed it. In 1926, his student, George Claude, well-known for his invention of the neon light and his pioneering work in cryogenics, began devoting his efforts to making OTEC a reality. In 1930, he succeeded in producing 22 kW in an open-cycle plant built on the Cuban coast.[1] [Superscripts refer to references cited at the end of the paper.] Because of the technical limitations of the day, his equipment consumed more power than it produced, and the project was eventually abandoned.

Interest in OTEC revived in the 1970s, as oil embargoes drove up the price of petroleum and threatened to interrupt its supply. The initial emphasis was on large, floating plants that might be miles from shore and capable of producing 250-400 MW of electricity for mainland power grids. As the problems of such plants became better understood, emphasis shifted to smaller (10-40 MW) plants built on the shores of tropical islands, where cold, deep water is often found close to shore, and which must import most if not all of its fossil fuel. In some versions of OTEC, these plants would also be capable of converting seawater to potable water, which is often in short supply on small islands. If such water can be sold at currently prevailing prices for fresh water, the economic viability of OTEC is greatly enhanced. Current research on OTEC is directed primarily at reducing the costs of plant and equipment, and on developing alternative cycles that are capable of producing potable water as a by-product, and which may be more economical.

The U.S. Department of Energy has supported research on three forms of OTEC: closed cycle, closed cycle with a flash evaporator (hybrid cycle), and open cycle. Of these, the latter two are capable of producing fresh water as a by-product.

*Work supported by the U.S. Department of Energy, Assistant Secretary for Conservation and Renewable Energy, Office of Solar Electric Technologies, Wind/Ocean Technologies Division, under Contract W-31-109-Eng-38.

Closed-cycle OTEC plants operate according to the same principles as conventional power plants. Tropical ocean water is used to evaporate a working fluid such as ammonia,* just as fossil or nuclear fuel is used to produce steam in a conventional steam boiler. The vaporized ammonia drives a turbine-generator to produce electrical power (Fig. 1). The low-pressure ammonia discharged from the turbine is condensed in a surface condenser against cold water drawn from 600-1000 meters below the surface. The condensed ammonia is then pumped back to the evaporator to begin the cycle again. This repeated cycle of boiling and condensing a contained working fluid to produce power is commonly called a Rankine cycle.

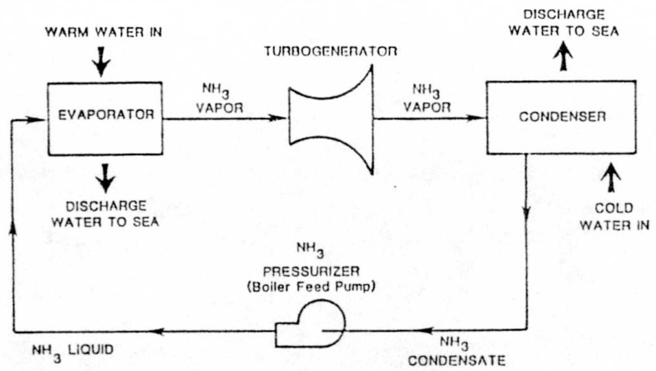

Figure 1 Closed-Cycle OTEC

In the hybrid-cycle variation of the closed cycle, warm seawater is first flash-evaporated at low pressure to produce water vapor. This vapor then gives up its thermal energy to the ammonia in the evaporator. Electrical power is produced as in the pure closed cycle. The condensed water vapor is collected as fresh water (Fig. 2).

The open cycle is the one Claude tried in Cuba and is shown schematically in Fig. 3. Warm seawater is flash-evaporated into steam under vacuum and passes directly through a large-diameter, low-pressure turbine to produce power. The exhaust steam is then condensed through direct mixing with cold seawater (the method used by Claude) or in a surface condenser (Fig. 4). The surface-condenser option has the advantage of producing fresh water as a by-product, as the condensed working fluid is distilled seawater.

The various cycles are discussed in more detail in Reference 2.

MAJOR RESEARCH EFFORTS

Since the revival of interest in OTEC, several major research efforts have been undertaken -- most notably by the U.S., France, and Japan -- to

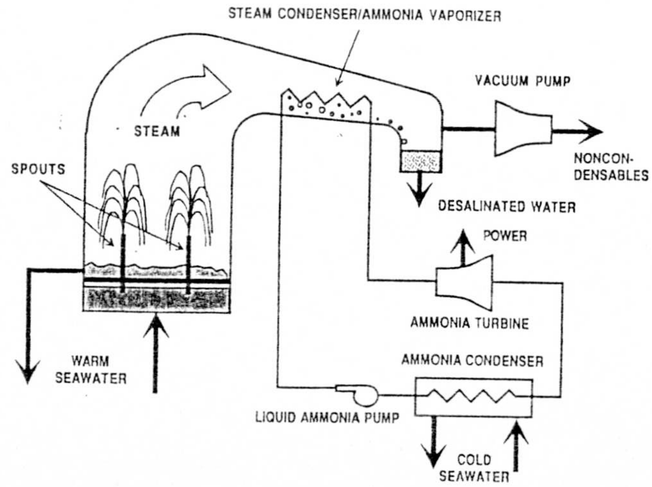

Figure 2 Hybrid-Cycle OTEC

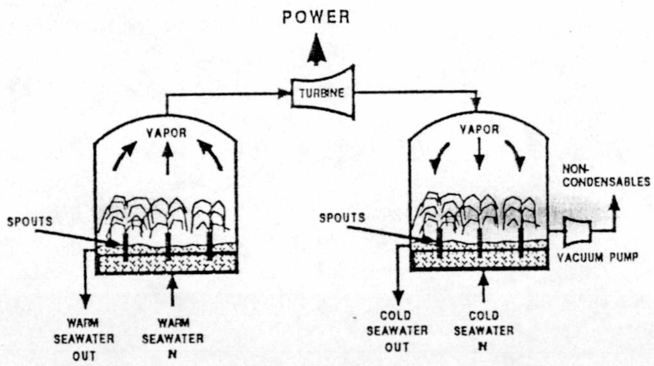

Figure 3 Open-Cycle OTEC

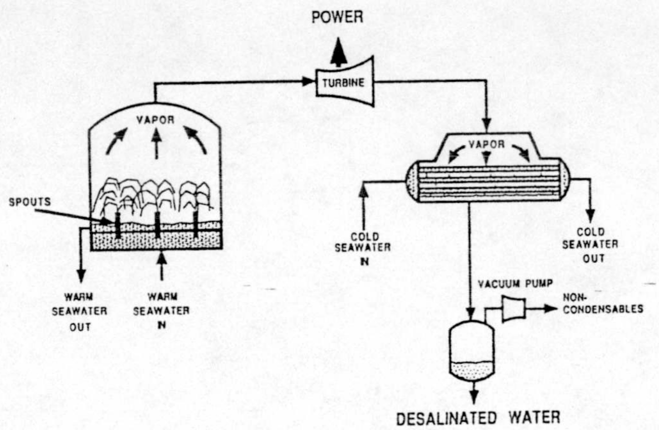

Figure 4 Open-Cycle OTEC with Surface Condenser

*The temperature range for OTEC is comparable to that for many refrigeration systems. Thus, refrigerants such as ammonia are used with closed-cycle OTEC because their physical properties are suited to thermodynamic cycles operating at these temperatures.

develop this technology to the point where it can be competitive with conventional power sources. Some of these are discussed briefly below.

Heat-Exchanger Development

Because of the low temperature differences inherent in an OTEC system, heat exchangers in a closed-cycle plant represent a large fraction of the total plant cost. Many designs were tested at Argonne National Laboratory in the late 1970s and early 1980s to identify those most promising.[3] A major finding of these tests -- and subsequent tests of larger units on a sea-going test vessel called *OTEC-1* -- was that performance of large exchangers could be predicted from data obtained from small units and even from single tubes. One concept -- called *compact* or *plate-fin* (Fig. 5) -- was found to be particularly promising, provided it could be built from aluminum and kept clean by non-mechanical means.

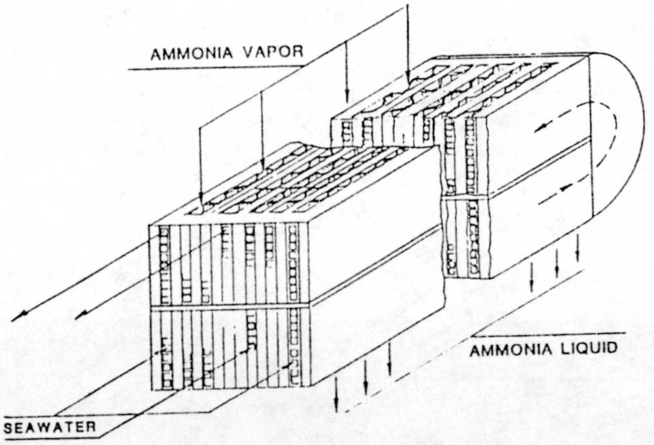

Figure 5 Compact Heat Exchanger

Biofouling-Control Research

Marine biofouling could quickly reduce the efficiency of an OTEC heat exchanger to unacceptable levels. Tests with warm and cold seawater of open-ocean quality were conducted by Argonne at the Natural Energy Laboratory of Hawaii (NELH) and elsewhere.[4] These tests demonstrated that intermittent chlorination for one hour per day at the environmentally acceptable level of 50-100 parts per billion would prevent fouling from warm seawater and even remove existing fouling. No fouling was observed on samples exposed to cold seawater.

Qualification of Aluminum

Although not traditionally used in seawater service, aluminum is an attractive material for OTEC heat exchangers because of its low cost, ease of fabrication, and good heat-transfer properties. Corrosion and biofouling tests were conducted in parallel at NELH.[4] These tests demonstrated: (a) uniform corrosion rates in both warm and cold seawater were compatible with long service lives for heat exchangers; (b) although pitting in cold seawater was a problem in some alloys, other alloys showed good resistance to pitting corrosion; and (c) cladding and other protective measures do not now appear to be cost-effective. Alloys tested in warm seawater were 3003, 5052, 5086, and 6063; all demonstrated acceptable corrosion resistance. Alloys tested in cold seawater were 3003, 5052 and 5086, with only minimal pitting observed. The best results obtained with alloy 5052, but because of the poor forming characteristics of 5052, alloy 3003 is potentially more attractive. More data on 3003 and other easily formed alloys would be desirable.

At the start of the OTEC program, it was believed that the heat exchangers would be the most costly portion of an OTEC plant, with some estimates ranging as high as 50% of total plant costs. The successful efforts in the above three developmental areas (heat exchangers, biofouling control, and qualification of aluminum) have reduced this figure to less than 30%. The most costly portion of an OTEC plant is now believed to be the seawater system.

Mini-OTEC

In 1979, a consortium that included the State of Hawaii, Lockheed, the Dillingham Corporation, Alfa-Laval, and others, demonstrated for the first time the technical feasibility of OTEC. In a plant located in a converted navy barge anchored about 2 km off the west (Kona) coast of Hawaii, 50 kW gross and 18 kW net electrical power were produced.[5]

Production of Fresh Water

In August of 1987, a team of engineers from the Solar Energy Research Institute (SERI) and Argonne National Laboratory (ANL), working on a joint OTEC research project at NELH, successfully produced 8000 gallons per day fresh water from the ocean, using the thermal energy stored in the seawater itself. The fresh water had a salinity (86 ppm) one-fifth that of tap water available at the site and is suitable for drinking or for raising crops. Although this particular apparatus (called the Heat and Mass Transfer Scoping Test Apparatus -- see Fig. 6) used an external source of power to pump the water, an actual OTEC plant would produce both power and water.[6]

Net Power Producing Experiment (NPPE)

Currently under design by SERI, ANL, and the Pacific International Center for High Technology Research (PICHTR) is an experiment to demonstrate the feasibility of the open-cycle OTEC process. It is similar in concept to the HMTSTA described above except that it will incorporate a large-diameter, low-pressure steam turbine to produce power from the flash-evaporated seawater. It is designed to produce 165-220 kW (gross) of electrical power and is scheduled for operation in the early 1990s. The NPPE will permit testing of both direct-contact and surface condensation, the

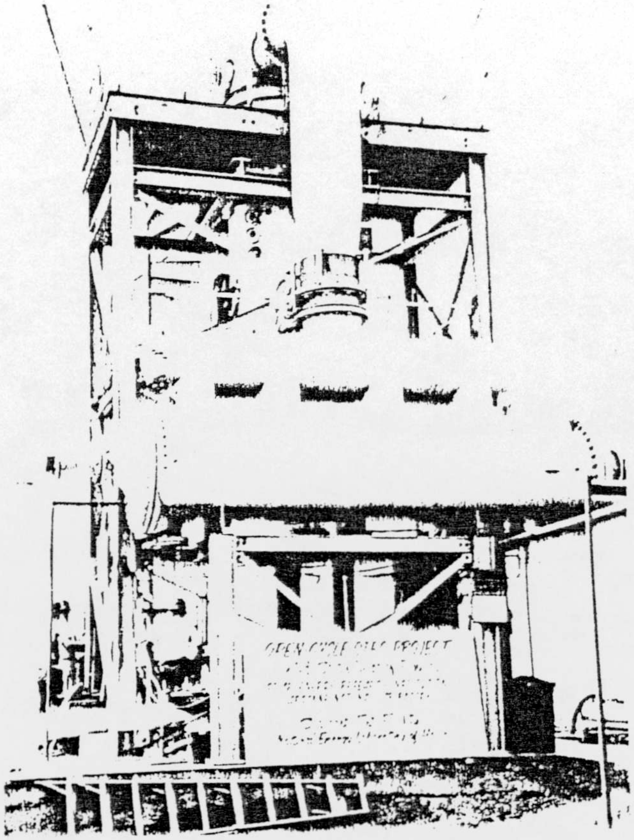

Figure 6 Heat and Mass Transfer Scoping Test Apparatus

latter required to produce fresh water as a by-product.

COMPARISON OF OTEC OPTIONS

Closed-cycle power-plant technology is proven for 10 MW shore-based plants (Fig. 7), and plant-design concepts have been developed.[7] The economics of such plants can be bracketed. These plants do not produce fresh water. They use ammonia, which can pose an environmental nuisance if accidently released. Chlorination is needed to keep the heat exchangers clean, but at levels that are presently considered environmentally acceptable. The thermodynamic efficiency might be improved by using an ammonia/water working fluid (Kalina cycle) to reduce the seawater requirements, but this cycle has not yet been tested under OTEC conditions.

The closed cycle with a flash-evaporator (hybrid cycle) produces both power and water with variable options. It has not been built as a system, but components have been tested and there are no major unknowns. This system uses ammonia but does not require chlorination.

The open cycle produces power and can produce fresh water with the substitution of a surface condenser for the direct-contact condenser. The feasibility of the open cycle has not been demonstrated, but it would be by the successful testing of the NPPE. The major unknown is the large-diameter, low-pressure steam turbine. Because the water is flash-evaporated, it requires no chlorination. Because the water vapor produces power directly, it uses no ammonia.

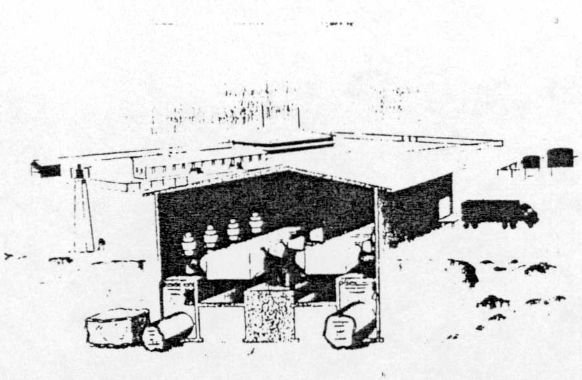

Figure 7 10 MW Shore-Based OTEC Plant

COMMERCIALIZATION OF OTEC

The future course for OTEC depends on both economic and technical factors. The main economic factors are: (1) the capital cost of such plants (presently high in relation to the cost of conventional plants), and further success in reducing these costs; (2) the costs of conventional fuels, which, in recent decades, have increased dramatically and then stabilized at levels about half their peak values; and (3) the marketability of fresh water produced by open- or hybrid-cycle OTEC. The technical consideration receiving the most attention currently is the development of a large-diameter, low-pressure turbine suitable for the open-cycle process. If other than shore-based plants are contemplated, developmental efforts will be required on mooring systems, the cold-water pipe, and transmission of power to mainline grids (or the use of power on plant ships). Before any commercial OTEC plant is built, it will probably be necessary to prove economic and operational feasibility with a smaller demonstration plant.

Many believe that OTEC will first be commercialized in small island markets where power and water are both in short supply and the OTEC resource abundant. Such plants would probably be in the range of 10-40 MW, although more development would be required for the seawater systems of a 40 MW plant. There are many potential markets in the Pacific basin and in the Caribbean that meet the requirements for the siting of a shore-based OTEC plant. These siting requirements are as follows:

- o A source of warm, nonpolluted surface seawater relatively close to shore. The mean annual water temperature should be at least 25°C. This temperature is typical of tropical locations.

- A steep offshore slope that reaches depths of 600-1000 meters within a few kilometers of shore. Since the water temperatures at these depths are the same worldwide (about 5°C), the temperature difference will be about 20°C, the minimum considered necessary for OTEC.

- An onshore site close to the water that is suitable for major construction activities, including excavation. It is also necessary that the elevation of the plant be as close to the sea level as possible to minimize pumping-power requirements.

- An offshore topology that is suitable for deploying the cold-water pipe. The current thinking envisions a buoyant plastic pipe anchored off the bottom by weights.

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