Ocean Thermal Energy Conversion

An Overview

On the cover: Photo on left—vertical-spout evaporator developed for an open-cycle ocean thermal energy conversion system. Photos on right, top to bottom—heat- and mass-transfer scoping test apparatus, turbine rotor, packing for the direct-contact condenser, and a sectional view of a plate-and-fin heat exchanger.

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Preface

Ocean thermal energy conversion, or OTEC, is a technology that extracts power from the ocean's natural thermal gradient. This technology is being pursued by researchers from many nations; in the United States, OTEC research is funded by the U.S. Department of Energy's Ocean Energy Technology Program. The program's goal is to develop the technology so that industry can make a competent assessment of its potential—either as an alternative or as a supplement to conventional energy sources. Federally funded research in components and systems will help bring OTEC to the threshold of commercialization. This publication provides an overview of the OTEC technology.

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Introduction

The oceans are the world's largest solar energy collector and storage system. On an average day, 60 million km^2 of tropical seas absorb an amount of solar radiation equivalent in heat content to about 245 billion barrels of oil. If less than 0.1% of this stored solar energy could be converted into electric power, it could supply the equivalent of more than 20 times the current total U.S. electricity consumption.

What Is OTEC?

The technology for this conversion is called OTEC, an acronym for ocean thermal energy conversion. OTEC plants can be built on land, on offshore platforms fixed to the ocean floor, on floating platforms anchored to the continental shelf, or on ships that move from place to place. Electricity generated by plants fixed in one place can be delivered directly to a utility grid. A submersed cable would be required to transmit electricity from an anchored floating platform to land. Moving ships could manufacture transportable products such as methanol, hydrogen, or ammonia on board. An OTEC system can also supply desalinated water. Moreover, the cold, deep seawater used in the OTEC process is nutrient-rich and can be used for culturing marine organisms and plant life near the shore or on land.

OTEC systems use the ocean's natural thermal gradient to drive a power-producing cycle. Three basic OTEC designs have been pursued: closed cycle, open cycle, and hybrid cycle. In the closed-cycle system, a working fluid with a low boiling point (such as ammonia or Freon®) is converted to vapor by indirect contact, through heat exchangers, with warm seawater drawn from just below the ocean's surface. In the open-cycle system, warm seawater becomes the working fluid when it enters a vacuum chamber and boils rapidly. In both systems, the resulting vapor drives a turbine-generator to produce electricity. The cycles are completed when cold seawater pumped from depths of 600–1000 m is used to recondense the vapor. If a heat exchanger such as a surface condenser is used in the open-cycle system, desalinated water is produced as a by-product. The hybrid-cycle system combines features of the open and closed cycles wherein seawater is flashed into steam, which is used to boil a closed-cycle working fluid. The hybrid-cycle system, thus, combines the desalinated water recovery aspects of an open-cycle system with the power-cycle components of a closed-cycle system. As long as the temperature between the warm surface water and the cold deep water differs by approximately 20°C, the system can produce significant amounts of net power. Figure 1 shows the distribution of the ocean temperature gradients.

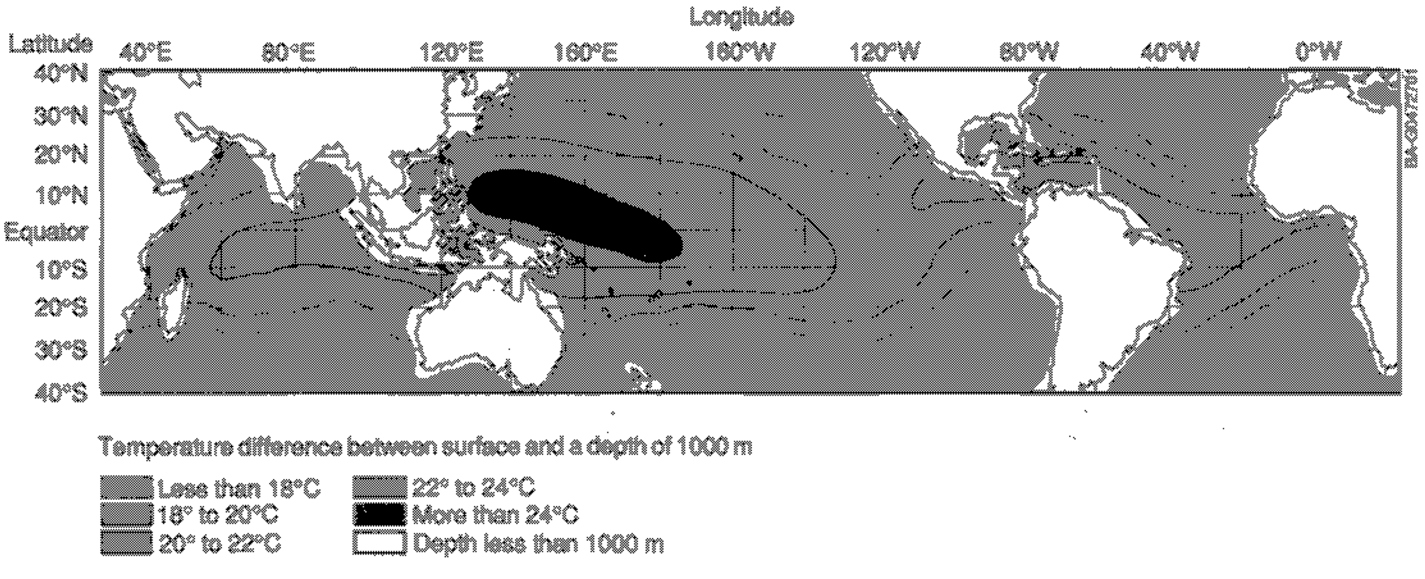


Figure 1 Ocean thermal resource map for 1000 m depth

OTEC systems are attractive because they use a clean, renewable source of energy. Current evidence suggests that OTEC plants affect the environment very little when compared with nuclear or fossil-fueled plants. The effects of plant discharge and carbon dioxide release are expected to be small or can be held to acceptable levels by design and operational control. Locating the plants judiciously can minimize other potential effects on the environment.

Current economics of energy production have delayed financing of a permanent, continuously operating OTEC plant. However, OTEC shows promise as an alternative for tropical island communities that rely heavily on imported fuel, including Hawaii and Puerto Rico. OTEC plants in these markets could provide islanders with much-needed power, as well as desalinated water and mariculture products, in the near term. By first addressing the technology and economics of OTEC plants for island communities, researchers will generate the information needed by future manufacturers of OTEC plants.

History of OTEC

The idea of tapping ocean thermal energy was first proposed by French physicist, Jacques Arsène d'Arsonval, in an 1881 *Revue Scientifique* article.[1] He envisioned a closed-cycle heat engine with ammonia as the working fluid but never tested it. In 1926, the idea captured the imagination of d'Arsonval's student, Georges Claude. Claude designed an open-cycle system and, using personal funds derived from his invention of the neon light, built an experimental system in 1930 at Matanzas Bay, Cuba.[2] The system used a cold-water pipe 1.6 m in diameter and 2 km in length to successfully bring cold seawater from a depth of more than 700 m. Claude's system generated 22 kW of electricity by using a special low-pressure turbine; however, the system operated on a temperature difference of only 14°C and consumed more power than it produced.

A storm destroyed Claude's cold-water pipe only a few days after the Matanzas Bay experiment began. In 1935, Claude began constructing another open-cycle plant, this time aboard a 10,000-ton cargo vessel moored off the coast of Brazil. Sea waves ripped apart the cold-water pipe during installation.[3] Nearly bankrupt, Claude was forced to stop work. He never achieved his goal of producing net power from an open-cycle OTEC system, but he did demonstrate that it is possible to integrate all the components into a working system.

Claude's work influenced the French government to continue research in open-cycle OTEC. In 1956, a French team designed a 3-$\mathrm{MW_e}$ open-cycle plant for Abidjan on Africa's west coast.[3] The team built a cold-water pipe that was 2.5 m in diameter and 4 km long, but it proved too difficult to deploy. Completion of the plant was also hindered by competition with inexpensive hydroelectric power.

The high cost of OTEC construction, especially of the cold-water pipe, delayed OTEC development for many years. The closed-cycle concept was revived in the early 1970s when impending worldwide energy shortages spurred further interest in OTEC.

The United States, Japan, France, the Netherlands, and several developing nations have investigated the potential of OTEC as a renewable energy option. Outside the United States, Japan has had the most active OTEC program. In 1981, the Tokyo Electric Power Company and Toshiba (subsidized by the Japanese Ministry of International Trade and Industry) built a 100-$\mathrm{kW_e}$ (gross) closed-cycle plant in the Republic of Nauru in the Pacific Ocean. This land-based plant had a cold-water pipe 945 m in length laid on the sea bed to a depth of 580 m. The plant used Freon® as a working fluid and titanium shell-and-tube heat exchangers. Although the Nauru plant was rated for a 14.9-$\mathrm{kW_e}$ net output, it surpassed engineering expectations by producing 31.5 $\mathrm{kW_e}$ of net power during continuous operating tests.[4]

Other countries, including France and the Netherlands, have used the knowledge gained from laboratory experiments to develop conceptual designs of their own commercial-scale plants. Construction of these plants remains on hold because of suppressed oil prices and the high-risk nature of OTEC technology.

The Federal Program

The current federal Ocean Energy Technology (OET) Program began in 1972 as the Ocean Energy Systems Program and was sponsored by the National Science Foundation. It was transferred to the Energy Research and Development Administration in 1975, which became the U.S. Department of Energy (DOE) in 1977. The OET Program is directed by DOE's Wind/Ocean Technologies Division.

The long-range mission of the OET Program is to develop ocean energy technology to where the commercial sector can assess whether the technology offers viable energy conversion alternatives, or supplements, to systems currently in use. Current research activities on components and small-scale experiments support this mission. Based on a careful evaluation of past activities, the OET Program strategy from 1985 to 1989 has been to focus on the technology that would allow industry to develop a 2–15-$\mathrm{MW_e}$ near-shore or land-based open-cycle OTEC system. The rationale behind this focus is that this size and configuration limit the extent of the technical uncertainty to be addressed. Also, the research and development activities will provide a data base for a system size and configuration that represents the initial market entry point for tropical island systems. Additionally, the data base developed from research on this size of system is modularly applicable to larger systems.[5]

The program is achieving this strategy by concentrating on specific technical objectives. The first is to experimentally verify the feasibility of the DOE-designed open-cycle OTEC system. The next objective is to determine methods that define and reduce the technical and cost uncertainties of OTEC systems. A common need for OTEC systems is the seawater supply system. The deep, cold seawater system, in particular, requires advanced concepts, designs, and installation techniques to reduce the technical risks and cost and to improve service life. A lower program priority is to determine the potential of other ocean energy technologies, such as wave energy conversion. Maintaining an awareness of how ocean energy technologies affect the environment and pursuing effective technology transfer to industry are also essential elements of the overall program strategy.

As noted, the first program priority is to prove the feasibility of open-cycle OTEC, which is being pursued through a net power-producing experiment (NPPE),[6-8] scheduled to begin operation in 1992. The experiment will be used to validate the computer models used in designing the NPPE. The experiment will be built at DOE's Seacoast Test Facility (STF) located at the Natural Energy Laboratory of Hawaii (NELH) at Keahole Point on the big island of Hawaii (see Figure 2). DOE and the state of Hawaii have jointly developed the capabilities needed to pump cold and warm seawater at this site, permitting testing of the open-cycle system's heat- and mass-transfer processes. A data base will be developed documenting how key components—such as the evaporator, condenser, mist eliminator, deaerator, and turbine—perform in a seawater environment. Materials performance and fabrication and installation techniques will also be evaluated.

Activities completed in recent years include designing, fabricating, installing, and operating a heat- and mass-transfer scoping test apparatus (HMTSTA) at the STF (Figure 3).[9] This apparatus validated the seawater performance of spout evaporators and direct-contact condensers crucial to open-cycle OTEC system performance. It also demonstrated for the first time in the OET Program that a prototype open-cycle OTEC system using a surface condenser can produce desalinated water.

DOE's OET Program activities are founded on a strong base of research and development. This base was used in 1979 when the state of Hawaii and Lockheed Corporation, with engineering and construction support from the Dillingham Corporation, built the first closed-cycle OTEC demonstration plant that produced a net output of electric power. Shown in Figure 4, Mini-OTEC was a closed-cycle plant mounted on a converted U.S. Navy barge moored about 2 km off Keahole Point. Mini-OTEC used a cold-water pipe measuring 0.46 m in diameter and 800 m in length to produce 52-kW$_e$ gross and 15-kW$_e$ net output.[10]

In 1980, DOE completed the construction of OTEC-1, a test bed for closed-cycle OTEC heat exchangers installed on board a converted U.S. Navy tanker (see Figure 5).[11] Results from OTEC-1 confirmed the methods that can be used to design commercial-scale heat exchangers. The test results

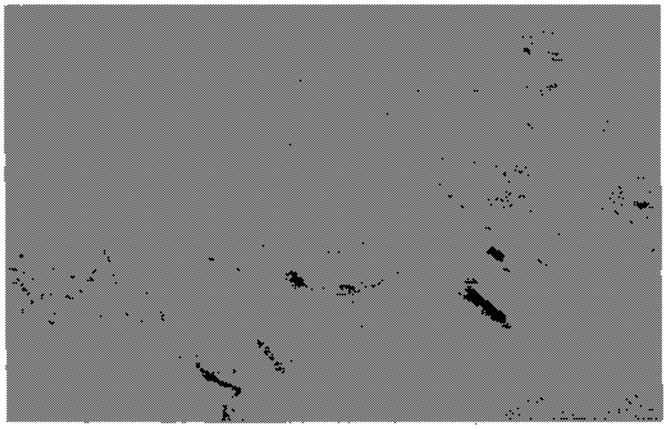


Figure 2 The Natural Energy Laboratory of Hawaii showing DOE's Seacoast Test Facility at bottom center. *(Courtesy of the NELH)*

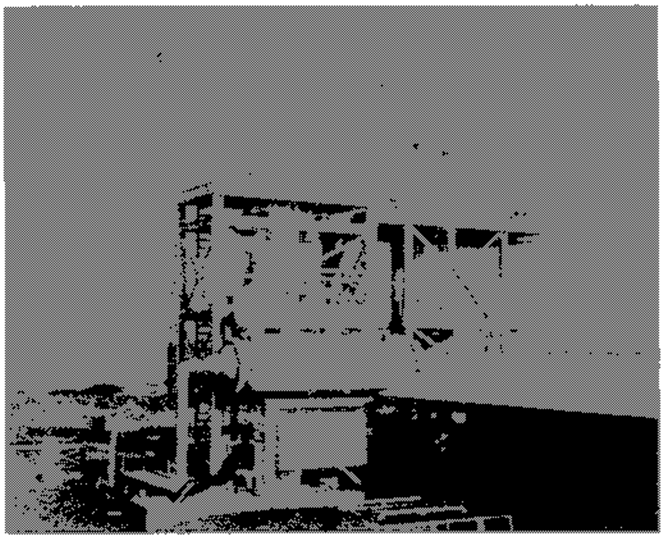


Figure 3 The heat- and mass-transfer scoping test apparatus at the Seacoast Test Facility

Figure 4 Mini-OTEC off Keahole Point, Hawaii *(Courtesy of the Lockheed Missiles and Space Co.)*

Figure 5 OTEC-1 at berth in Pearl Harbor, Hawaii *(Courtesy of Global Marine Drilling Company)*

also demonstrated that OTEC systems can operate from slowly moving ships and with very little effect on the environment. The OTEC-1 experiment, the first integrated system in DOE's test program, was successfully concluded in 1981.

In 1980, two laws were enacted to promote the commercial development of the OTEC technology. The Ocean Thermal Energy Conversion Act (PL 96-320, later modified by PL 98-623) established licensing procedures and authorized loan guarantees for OTEC facilities. The Ocean Thermal Energy Conversion Research, Development, and Demonstration Act (PL 96-310) authorized a comprehensive program to aid the early deployment of OTEC power plants. This law set goals for the installed capacity for OTEC systems, beginning with 100 MW_e by 1986 and reaching 10 GW_e by 1999. However, the economic climate of the United States has changed, and the cost of fossil fuels has dropped dramatically since these goals were established. As a result, a lower rate of market penetration is expected, and the total installed capacity goals are not expected to be met within the period set forth in PL 96-310.

Since these laws were enacted, DOE has shifted its emphasis from commercialization to high-risk, high-payoff research and development that private industry is unlikely to pursue. Under this modestly funded program, researchers are continuing to make important strides in developing both closed- and open-cycle OTEC systems.

Chapter 1

Power Cycles

As previously mentioned, the warm and cold seawater circulating through an OTEC plant can drive two kinds of power-producing cycles: closed and open, which can be combined into hybrid systems. These cycles can also be used with other thermal resources, such as in a fossil-fueled-plant bottoming cycle.

Closed-Cycle OTEC

As discussed in the Introduction, power is generated in a closed-cycle OTEC system when warm seawater drawn from the ocean's top layers enters a heat exchanger and vaporizes a working fluid such as ammonia or Freon®. The vapor then passes through a turbine coupled to a generator that produces electricity. The cycle is completed when cold seawater from the ocean's depths recondenses the vapor in a surface condenser (see Figure 1.1). Mini-OTEC demonstrated that floating closed-cycle OTEC systems can produce net power;[10] however, issues of attaining optimum efficiency and making the system cost-effective remain.

Several large plant system concepts were developed and evaluated in the late 1970s and early 1980s.[12] Research on closed-cycle OTEC systems culminated in the completion of a preliminary design for a 40-MW_e plant sited near Kahe Point on the Hawaiian island of Oahu.[13] This design defined the performance and cost of systems based on using commercially available components and construction methods. The power system accounts for about half of the overall cost of a closed-cycle OTEC plant, and its performance establishes the design requirements for the rest of the plant. The power system is made up of heat exchangers, a turbine/generator, and a complement of other mechanical equipment and piping. Heat exchangers influence the major performance and cost issues relating to closed-cycle systems.

The current technology of surface heat exchangers is such that they must have large areas to transfer enough heat at OTEC's small temperature difference. Several heat exchanger designs are shown in Figure 1.2. One form of conventional heat exchanger uses a shell-and-tube configuration in which seawater flows through the tubes, and the working fluid evaporates or condenses in a shell around them. A way to enhance this design is to use fluted tubes: the working fluid flows into the grooves and over the crests, producing a thin film that evaporates more effectively. In an advanced

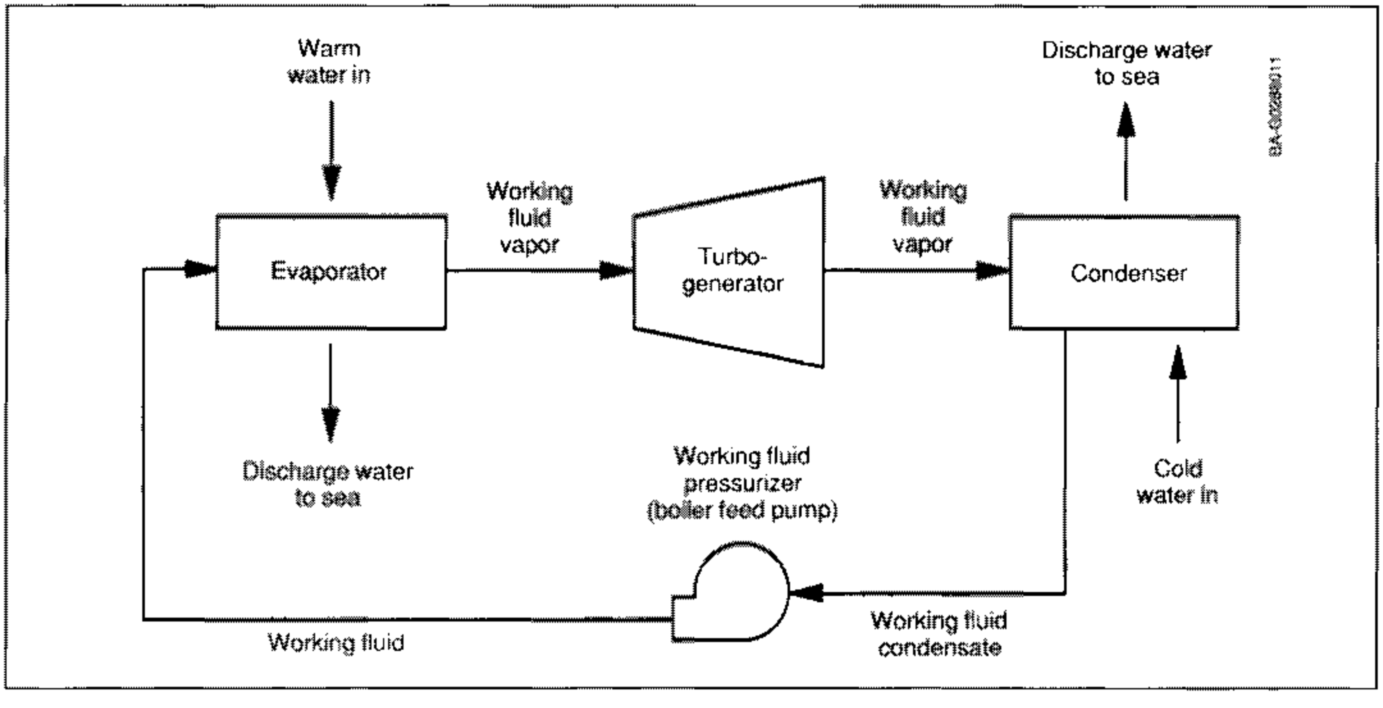
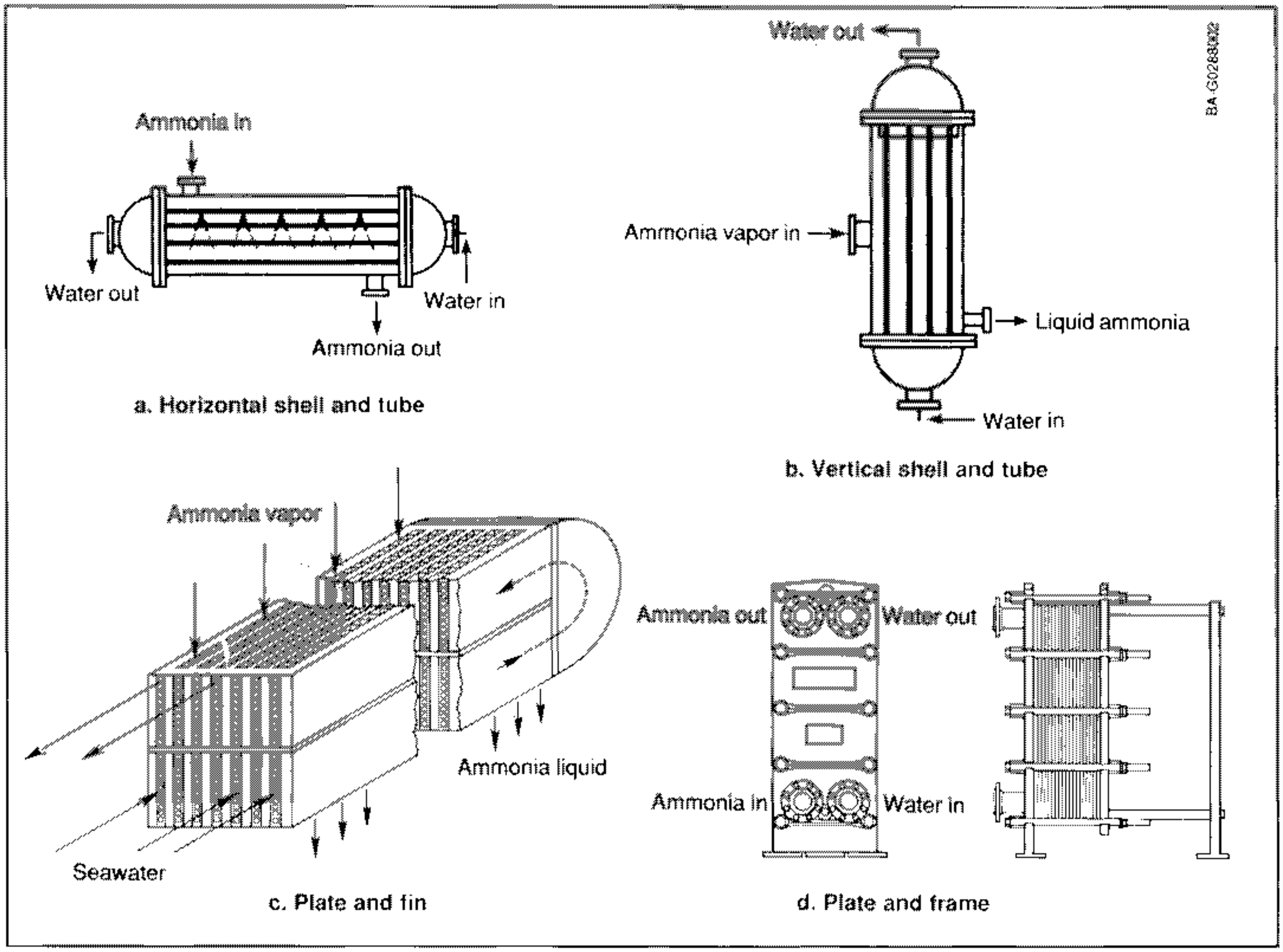


Figure 1.1 A closed-cycle OTEC system



a. Horizontal shell and tube

b. Vertical shell and tube

c. Plate and fin

d. Plate and frame

Figure 1.2 Several concepts for OTEC surface heat exchangers[12]

plate-and-fin design (Figure 1.2c), working fluid and seawater flow through alternating parallel plates; fins between the plates enhance the heat transfer.

Titanium was the original material chosen for closed-cycle heat exchangers because it resists corrosion. However, it is an expensive option for plants that use large heat exchangers. Corrosion-resistant copper-nickel alloys, which can be used to protect platforms and cold-water pipes, are not compatible with ammonia, the most common working fluid. A suitable alternative to these materials may be aluminum. In tests conducted by Argonne National Laboratory (ANL), brazed-aluminum tubes and channels similar to those used in full-size heat exchangers performed well under marine conditions. Results indicate that selected aluminum alloys may last 20 years in seawater.[14]

ANL researchers are investigating ways to prevent biofouling, the layer of slime and marine organisms that can grow quickly on surfaces exposed to warm seawater. In heat exchangers, this buildup reduces the heat-transfer efficiency. Laboratory experiments indicate that biofouling can be prevented by mixing chlorine in the pipes intermittently, totaling one hour a day, at a concentration of 70 ppb. This is well below the level of 200 ppb for two hours per day allowed by the U.S. Environmental Protection Agency.[15]

The turbine/generator and associated mechanical equipment are similar to that used in the refrigeration/air-conditioning and power generation industries. When refrigerants such as Freon® and ammonia are used as working fluids, the temperatures and pressures encountered are similar to those in a refrigerator. Thus, the hardware and materials-handling problems are readily solved, and no research is needed in these areas until the system becomes very large.

Open-Cycle OTEC

Open-cycle OTEC systems use vaporized seawater as the working fluid. As shown in Figure 1.3, warm seawater drawn from near the ocean's surface is pumped into a vacuum chamber where a small amount is flash-evaporated into low-density steam that drives a low-pressure turbine. The steam is then condensed by cold seawater drawn from the ocean's depths—using either direct-contact condensers or

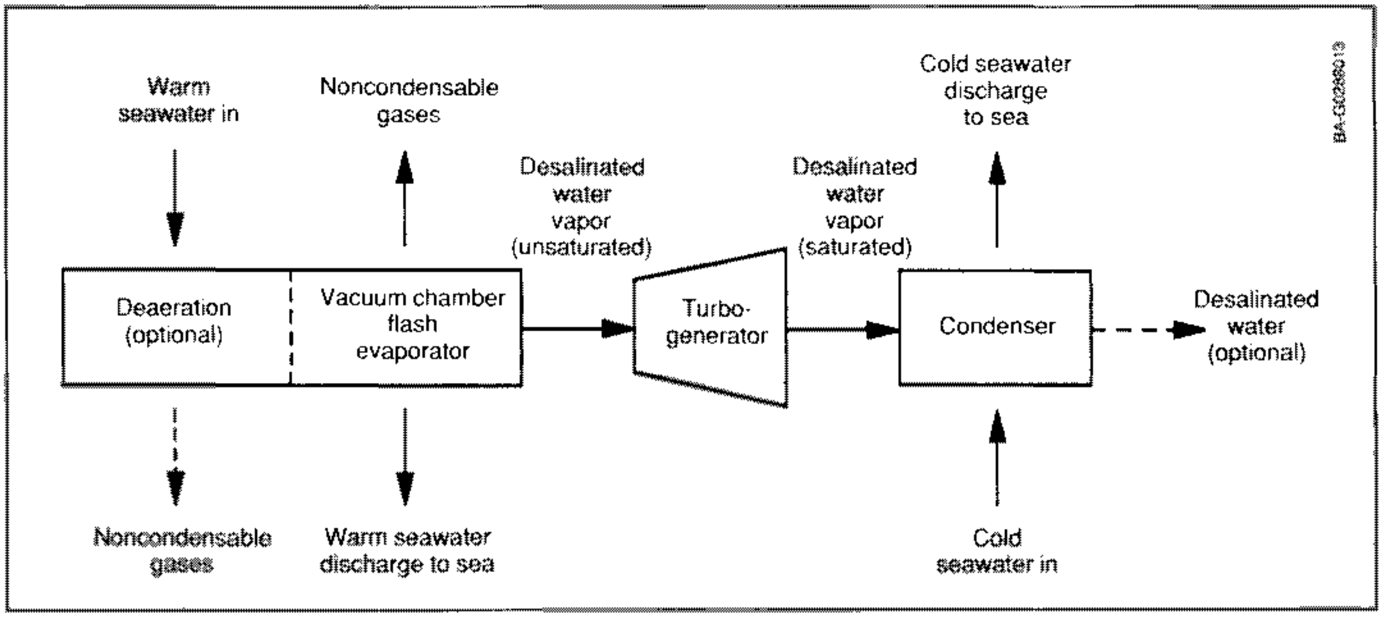


Figure 1.3 An open-cycle OTEC system

indirect contact through surface condensers—and discharged from the plant. With the use of surface condensers, open-cycle plants can produce commercially valuable desalinated water.

Open-cycle flash-evaporators include those with open-channel flow, falling films, and falling jets. These conventional evaporators typically perform to within 70% to 80% of the maximum thermodynamic performance at acceptable hydraulic losses. Research at the Solar Energy Research Institute (SERI) led to the development of a vertical-spout evaporator that can perform to within 90% of the thermodynamic limit. In this evaporator, shown in operation in Figure 1.4, water is drawn upward through a vertical pipe (a spout) and violently sprayed outward by escaping steam.[16] To enhance performance, the spray may fall on screens that further break up the droplets and increase the evaporation rate. To avoid pressure loss, the evaporator has simple intake and exit systems that separate the steam from the discharge. Steam continues through the system, and the remaining seawater is discharged from the bottom of the evaporator. This design was tested using fresh water in the SERI laboratory and using seawater at the HMTSTA and was found to be equally effective under both circumstances.[17]

Violent flashing in a spout evaporator causes seawater droplets to be entrained by the steam. If not removed, these droplets can cause erosion and stress-corrosion cracking in turbine blades and contaminate the desalinated water discharge as well. Seawater droplets can be removed in sufficient quantity by passing the steam through the commercially available mist eliminators used in the chemical industry.[18]

After the droplets are removed, steam flows through large, low-pressure turbines, entering at a pressure of about

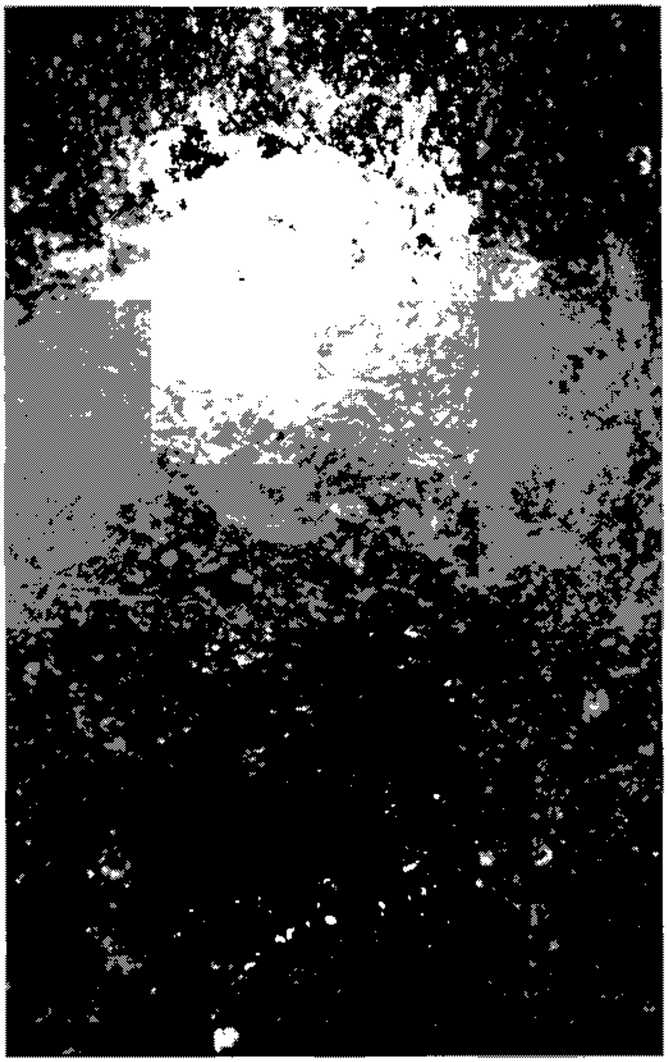


Figure 1.4 SERI's vertical-spout evaporator

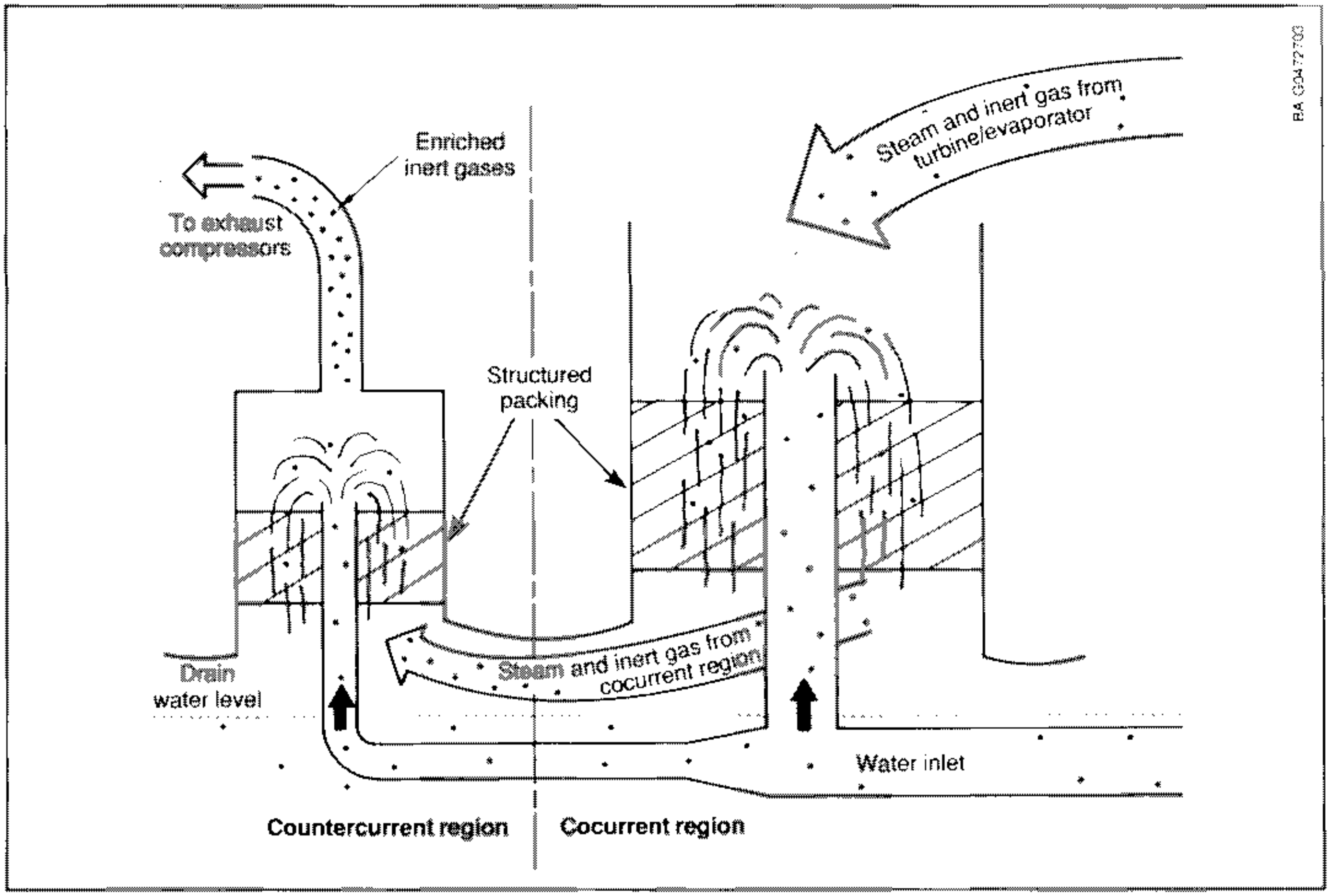


Figure 1.5 A two-stage direct-contact condenser with typical OTEC parameters

2.4 kPa. These turbines must be able to handle the large steam flows necessary to produce significant electric power. In a 1979 design study, Westinghouse Electric Corporation concluded that the most reliable and cost-effective turbine for a 100-MW_e (net) plant would be a low-speed (200 rpm) unit measuring 43.6 m in diameter,[19] which requires development. The largest, currently available turbines are the multistage turbines used in nuclear or coal-fired power plants. The low-pressure stages of these turbines typically operate at conditions close to those needed in an open-cycle OTEC plant. The rotor that makes up the last stage (which is typically about 5 m in diameter) together with a modified stator can produce about 2.5 MW of electricity (gross).[20] Larger plants will require either several turbines operating in parallel or major advances in turbine technology leading to larger rotors. Studies show that turbine configurations other than axial may also prove cost-effective for large open-cycle systems.[21]

After steam passes through the turbines, it can be condensed in direct-contact condensers or surface condensers. Researchers through DOE's OET Program have tested direct-contact condensers, which condense steam directly with cold seawater. Direct-contact condensers do not have the intermediate solid wall of a surface condenser and, therefore, provide more effective condensation.[22] In one design—a two-stage condenser developed at SERI (see Figure 1.5)—cold seawater is distributed through two open-ended plastic cylinders filled with a commercially available structured packing material. About 80% of the steam is condensed as it flows through the first cylinder in the same direction as the cold seawater. The remaining steam is routed into the bottom of the second cylinder and flows through it in the opposite direction to the seawater. At the top of the second cylinder, a vacuum system pumps out the noncondensable (inert) gases along with any uncondensed steam.

Surface condensers keep the cooling seawater separate from the spent steam during the condensation phase. By using indirect contact, the condensers produce desalinated water that is relatively free of seawater impurities. The surface condensers considered for use in OTEC systems (see Figure 1.2) are similar to those used in conventional power plants; however, these surface condensers must operate under lower pressures and with higher amounts of noncondensable gases in the steam. Prototypes continue to be tested and verified under marine conditions, with special attention paid to the problems of corrosion and biofouling.[14]

Steam in the open-cycle system contains noncondensable gases that can interfere with power production. These gases—oxygen, nitrogen, and carbon dioxide—are released

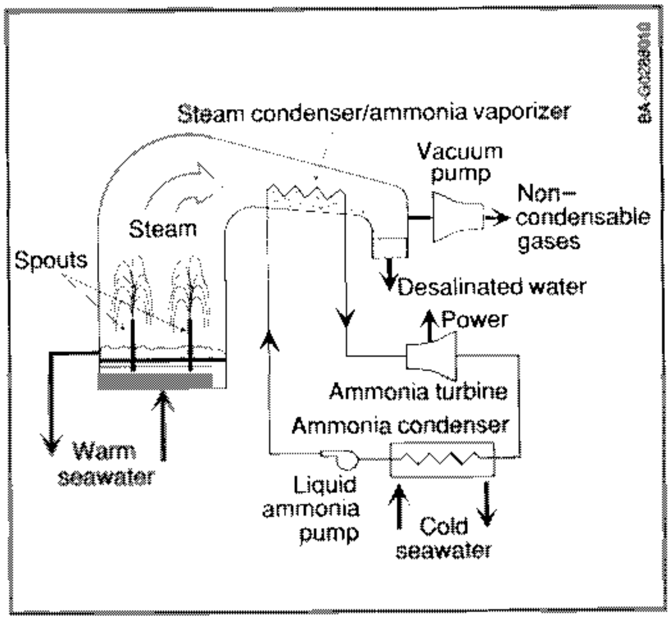


Figure 1.6 A hybrid OTEC system

from the seawater when it is exposed to low pressures under vacuum. Air also enters the open-cycle vacuum vessel through leaks, although good construction techniques can reduce the rate of air leakage to very low levels. Unless these gases are removed from the vacuum chamber, they can interfere with condensation, particularly with surface condensers, by blanketing the condensing surfaces or can even build enough pressure to stop evaporation. An exhaust compressor can remove these noncondensable gases. The maximum power required to run the compressor is estimated to be about 10% of the gross power generated by the system.[23]

Hybrid OTEC Systems

Another OTEC option is the hybrid open-cycle/closed-cycle system, which can efficiently produce electricity and desalinated water. In this concept, warm seawater enters a vacuum chamber where it is flash-evaporated into steam, which is similar to the open-cycle evaporation process. The steam vaporizes the working fluid of a closed-cycle loop on the other side of an ammonia vaporizer; the vaporized fluid then drives a turbine that produces electricity.[24] The steam condenses within the heat exchanger to produce desalinated water. Figure 1.6 shows this process.

The hybrid cycle benefits directly from the research done on spout evaporators and uses the ammonia condenser technology developed for closed-cycle systems. The new component in this concept is the ammonia vaporizer, which is heated by condensing low pressure steam. Also, because the volume of condensing steam is much less than it is in the open-cycle system, the condenser can be smaller. Because no seawater touches the heat exchanger, the brazed-aluminum plate-fin construction (shown in Figure 1.7) may be suitable for this application.

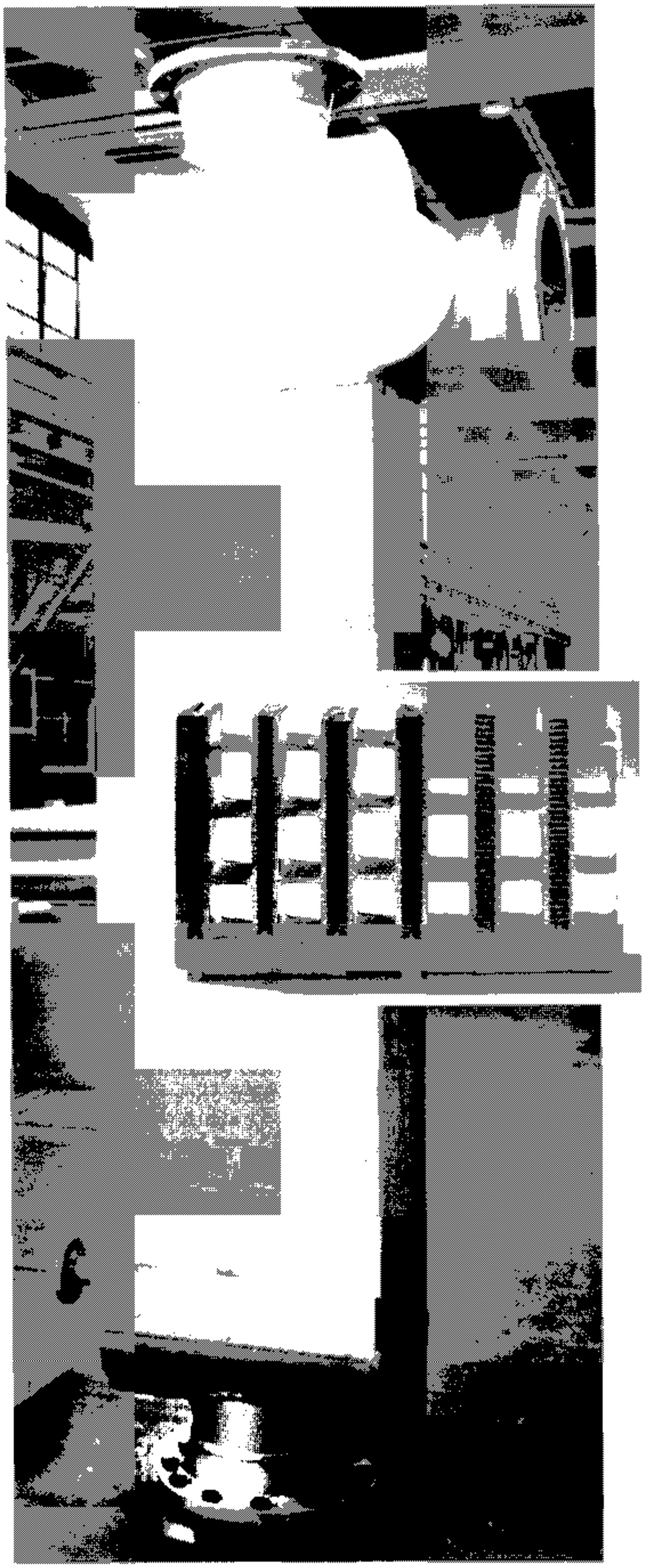


Figure 1.7 A plate-and-fin heat exchanger. The inset shows cross section of fins *(Courtesy of ANL)*

Figure 1.8 Laboratory-scale heat- and mass-transfer system at SERI

The hybrid-cycle system uses turbines similar to those required for closed-cycle systems and vacuum-purge systems similar to those required for open-cycle systems.

Enhanced OTEC Systems

In some locations, the output of OTEC plants could be enhanced by using other thermal resources. Conventional power plants located on shore could provide higher temperature warm water for an OTEC operation. At Adak, Alaska, warm water could be drawn from a natural geothermal resource, and cold water could be supplied directly from the ocean's surface.[25] However, locations for these enhanced systems are limited, and the economic feasibility of such systems remains unproven.

Closed-cycle and open-cycle systems are within reach of efficient power generation and ultimate commercialization. Those working in the DOE OET Program will continue to investigate and monitor developments in innovative alternatives, such as hybrid and enhanced systems.

Current Activities in Power Cycles

The DOE OET Program is funding the development and testing of open- and hybrid-cycle OTEC systems. Laboratory experiments are done in the SERI heat- and mass-transfer research facility and in the ANL heat-exchanger test facility, portions of which are shown in Figures 1.8 and 1.9, respectively. In addition, researchers are using computer models to help develop components, including deaerators, evaporators, mist eliminators, turbines, and condensers. Scaled experiments planned for the STF will help researchers establish whether open-cycle systems can produce significant amounts of net power.

Current efforts in the program are focused on the NPPE.[17] A critical activity is to develop a low-pressure steam turbine to produce nominally 165 kW of electricity (gross). Selecting this power level was based primarily on the available seawater system capacity, funding, and the need to significantly reduce the risk of the experiment while providing the technical data needed for developing larger systems. Steps toward developing the NPPE turbine began with a workshop, held in

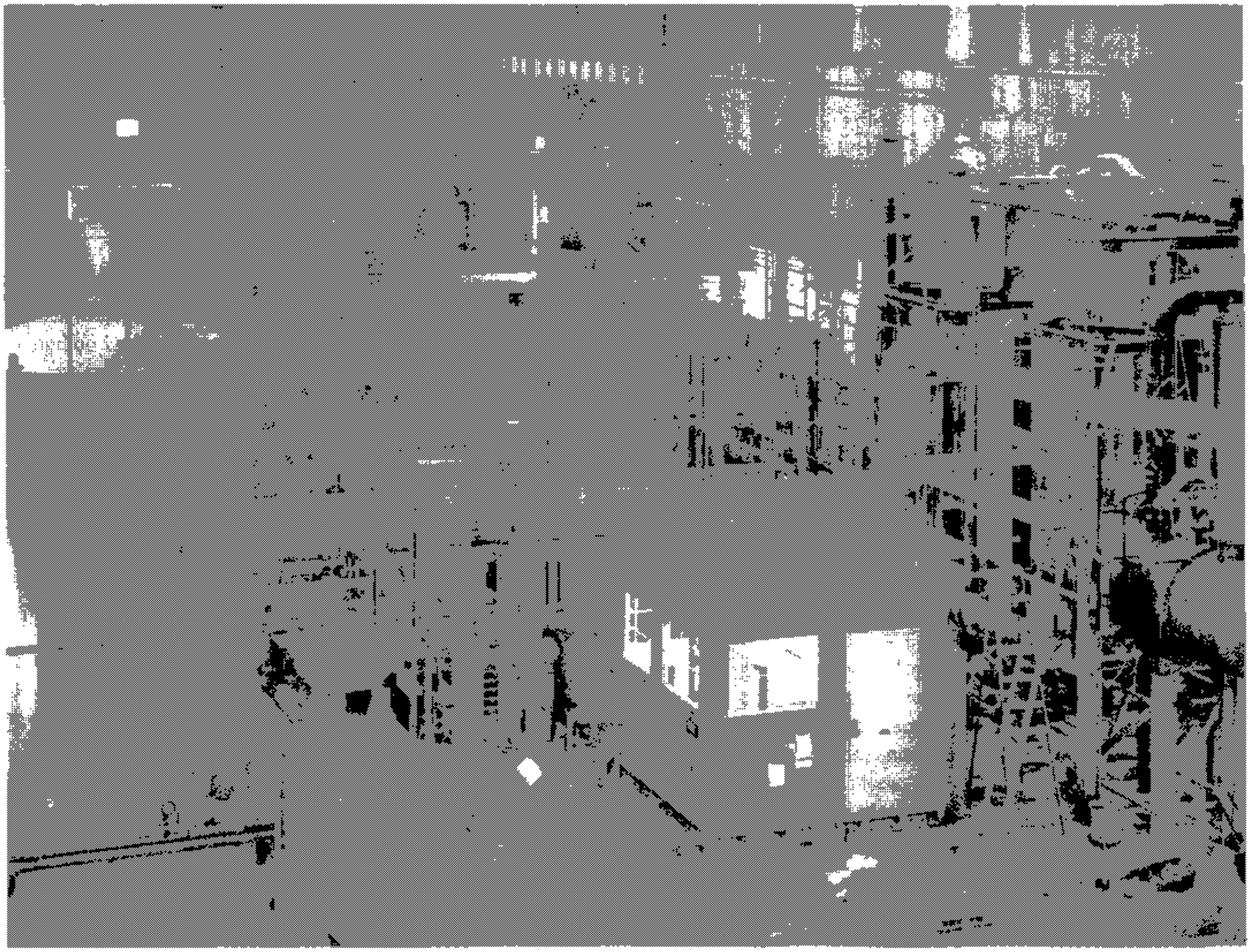


Figure 1.9 Heat exchanger test facility at Argonne National Laboratory *(Courtesy of ANL)*

November 1986, where industry experts identified state-of-the-art designs, fabrication techniques, and problem areas of low-pressure steam turbines. In general, the workshop attendees concluded that designing, fabricating, and installing a test model turbine for the NPPE was feasible using existing turbine technology. In fact, existing rotors could be used in systems up to a 2.5 MW; however, stators need to be developed.[26]

Based on the recommendations of the turbine workshop participants, a dual approach was adopted for developing the NPPE turbine. One approach will examine adapting existing hardware, and the other will consider using established technology to design a turbine specifically for the experiment. Both approaches will be carried to a preliminary design stage, where the option will be chosen that best meets the needs of the experiment and provides data that industry can use to design and build larger systems.

Meanwhile, researchers will explore innovative turbine concepts that might significantly reduce the cost of electricity from larger open-cycle OTEC plants.[21]

Chapter 2
Plant Design and Location

Studies indicate that commercial OTEC facilities could be located on land or near the shore, on platforms attached to the continental shelf, or on moored or free-floating facilities in deep ocean water. Basic considerations for plant design and location include

- A stable environment for system operation
- A constant source of both warm and cold water with a minimum temperature difference of 20°C
- A cost-effective way to deliver power and complementary products.

Land-based and near-shore facilities are currently considered the most probable for OTEC market penetration and early development.

Land-Based and Near-Shore Facilities

Land-based and near-shore facilities offer three main advantages over those located in deep water. Plants constructed on or near land will not require sophisticated mooring, lengthy power cables, or the more extensive maintenance associated with open-ocean environments. They can be installed in sheltered areas so that they are relatively safe from storms and heavy seas. Electricity, desalinated water, and cold, nutrient-rich seawater could be transmitted from near-shore facilities via trestle bridges or causeways. In addition, land-based or near-shore sites would allow OTEC plants to operate with related industries such as mariculture or those that require desalinated water.

These plants could be built using today's technology with only minor modifications. Favored locations include those with narrow shelves (volcanic islands), steep (15–20 deg) offshore slopes, and relatively smooth sea floors. These sites would minimize the length of the cold-water intake pipe. A land-based plant could be built well inland from the shore, offering more protection from storms, or on the beach, where the pipes would be shorter. In either case, the ease of access for construction and operation would help lower the cost of OTEC-generated electricity.

As previously mentioned, these land-based or near-shore sites can support mariculture. Mariculture tanks or lagoons built on shore allow workers to monitor and control miniature marine environments. Mariculture products can be delivered to market with relative ease via railroads or highways.

One disadvantage of land-based facilities arises from the turbulent wave action in the surf zone. Unless the OTEC plant's water supply and discharge pipes are buried in protective trenches, they will be subject to extreme stress during storms and prolonged periods of heavy seas. Also, the mixed discharge of cold and warm seawater may need to be carried several hundred meters offshore to reach the proper depth before it is released. This arrangement would require additional expense in construction and maintenance.

OTEC systems can avoid some of the problems and expenses of operating in a surf zone if they are built just offshore in water depths ranging from 10 to 30 m.[13] This type of plant would use shorter (and therefore less costly) intake and discharge pipes, which would avoid the dangers of turbulent surf. The plant itself, however, would require protection from the marine environment, including breakwaters and erosion-resistant foundations, and the plant output would need to be transported to shore.

Experience shows that the potential problems of near-shore or land-based sites need not hinder OTEC development. The Japanese successfully tested a land-based system in the Republic of Nauru.[4] This 100-kW_e (gross) plant, shown in Figure 2.1, demonstrated that shore-based closed-cycle systems can produce net power. The original seawater supply system of the land-based STF has been operating almost continuously since 1982; Figure 2.2 shows the point at which these pipes supplying seawater to the STF cross the surf

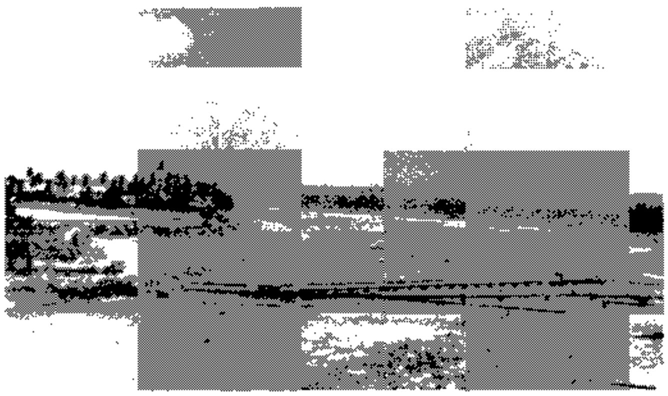


Figure 2.1 The land-based 100-kW_e (gross) OTEC plant at Nauru *(Courtesy of Tokyo Electric Power Co., Inc.)*

Figure 2.2 Three PVC seawater pipes crossing the surf zone at the Natural Energy Laboratory of Hawaii *(Courtesy of NELH)*

zone. The success of these facilities indicates that land-based or near-shore locations offer a feasible choice for OTEC plants.

Shelf-Mounted Facilities

To avoid the turbulent surf zone as well as to have closer access to the cold-water resource, OTEC plants can be mounted to the continental shelf at depths of up to 100 m. A shelf-mounted plant could be built in a shipyard, towed to its site, and fixed to the sea bottom. This type of construction is already used for offshore oil rigs. The additional problems of operating an OTEC plant in deeper water, however, may make shelf-mounted facilities less desirable and more expensive than their land-based counterparts. Problems with shelf-mounted plants include the stress of open-ocean conditions and more difficult product delivery. Having to consider strong ocean currents and large waves creates additional engineering and construction expense. Platforms require extensive pilings to maintain a stable base for OTEC operation. Power delivery could also become costly because of the long underwater cables required to reach land. For these reasons, shelf-mounted plants are less attractive for near-term OTEC development.

Floating Facilities

Floating OTEC facilities could be designed to operate offshore. Such a plant is conceptualized in Figure 2.3. Although potentially preferred for systems with a large power capacity, floating facilities present several difficulties. This plant design will be more difficult to stabilize, and its difficulty to moor in very deep water may create problems with power delivery. Cables attached to floating platforms will be more susceptible to damage, especially during storms. Cables at depths greater than 1000 m will be difficult to maintain and repair. Riser cables, which span the distance between the sea bed and the plant, will need to be constructed to resist entanglement.

Figure 2.3 Design for a floating, 100-MW$_e$ open-cycle OTEC plant[19]

As with the shelf-mounted plants, floating plants will need a stable base for continuous OTEC operation. Major storms and heavy seas can break the vertically suspended cold-water pipe and interrupt the intake of warm water as well. To help prevent these problems, pipes can be made of relatively flexible polyethylene attached to the bottom of the platform and gimballed with joints or collars, as was done with OTEC-1. Pipes may need to be uncoupled from the plant to prevent damage during storms. As an alternative to a warm-water pipe, surface water can be drawn directly into the platform; however, engineers would need to locate the intake carefully to prevent the intake flow from being interrupted during heavy seas when the platform would heave up and down significantly.

If a floating plant is to be connected to power delivery cables, it will need to remain relatively stationary. Mooring would be an acceptable method, but current mooring technology is limited to depths of about 2000 m. Even at shallower depths, the cost of mooring may prohibit commercial OTEC ventures.

An alternative for deep-water OTEC may be drifting or self-propelled plantships. These ships would use their net power on board to manufacture energy-intensive products such as hydrogen, methanol, or ammonia.[27]

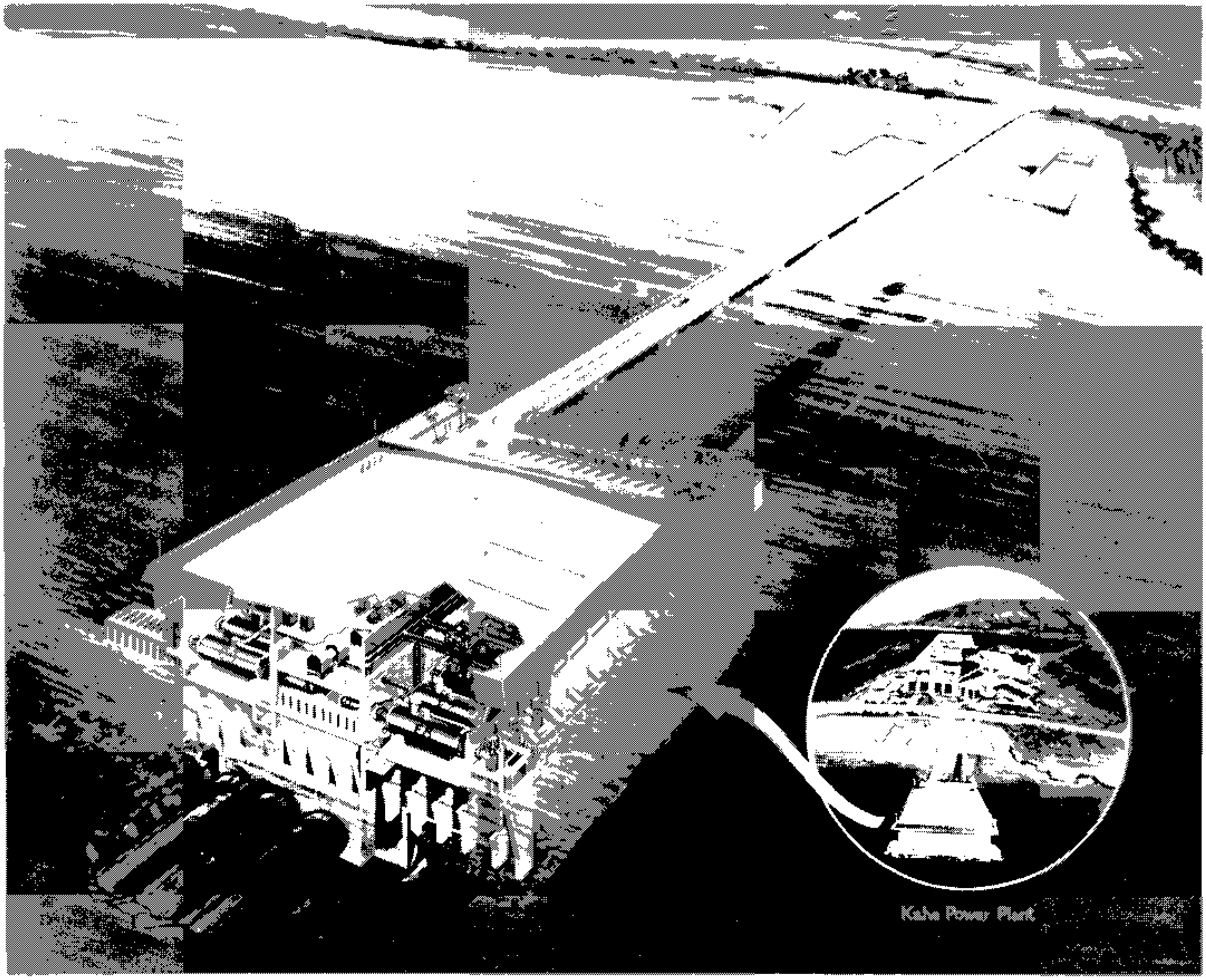


Figure 2.4 Artist's rendering of a 40-MW_e closed-cycle OTEC plant[13]

Development of OTEC Power Plants

As previously mentioned, commercial OTEC plants must be placed where the temperature of the warm, surface seawater differs about 20°C from that of the cold, deep water. Storm frequency; prevailing currents; and political, legal, social, and economic factors also need to be considered.

The natural ocean thermal gradient necessary for OTEC operation is generally found between the latitudes of 20 deg N and 20 deg S (see Figure 1). Within this tropical zone are portions of two industrial nations (the United States and Australia), 29 territories, and 66 developing nations. Of all these possible sites, tropical islands with growing power requirements and a dependence on expensive imported oil will be the most likely early markets for OTEC development.

The DOE OET Program is working to provide industry with enough information to develop and deploy an OTEC system that would be competitive with conventional power systems in island markets. A long-range program goal for the capital cost of an OTEC system is \$3,200/kW_e, projected to be realized after 10 years of continued aggressive technology development.[5] But even though many important technical achievements have occurred, the lack of firm data on the performance and the cost of a fully operational plant hinders commercial development. To help fill this void, the DOE OET Program funded design studies and cost analyses for a "proof of concept" closed-cycle OTEC system.[13] The studies culminated in a preliminary design for a 40-MW_e (net) closed-cycle plant that would be located off Kahe Point on the island of Oahu in Hawaii. An artist's rendering is shown in Figure 2.4.

The Kahe Point plant was designed by the Ocean Thermal Corporation under a contract with DOE, who shared the cost. In this near-shore concept, a concrete platform would be built in a safe harbor, then floated to within 550 m offshore and sunk 15 m to the sea bed. A vertical breakwater would allow the structure to withstand stresses from storms, tsunamis, tides, and currents; rubble piled around the foundation would help prevent erosion. A trestle would connect the platform to shore.

The cold-water pipe, measuring 3670 m in length, would be constructed in two segments. A near-shore segment with a diameter of 7.5 m would be deployed along with the discharge pipes in a post-tensioned concrete pipeline. Over an escarpment and at greater depths, a fiber-reinforced plastic segment with regularly spaced bellow joints would be used.

Warm water would be supplied through a large, rectangular opening in the shore side of the plant; the natural warm- and cold-water temperature difference of 21.4°C would be raised 1.6°C by adding warm discharge water from a nearby oil-fired power plant. Intake velocities for both warm and cold water would be limited to about 0.3 m/s to reduce the impingement and entrainment of marine organisms. To prevent cooling and disturbance of the surface water around the plant, the discharge stream would be carried to a depth of 30 m before release.

As specified in the original design, the power system would consist of four 10-MW_e modules. Each module would contain four shell-and-tube heat exchangers (two evaporators and two condensers), an ammonia working fluid, and a four-stage turbine that would generate 13-MW_e gross and 10-MW_e net output. The total plant net output could reach 45.8 MW_e in summer.

The Ocean Thermal Corporation projected an installed cost of $430 million for this pilot plant design. Heat exchangers account for 16% of the cost; pipes contribute 36%, and the platform, 24%. The unit capital cost was estimated at $12,200/$kW_e$.

Fully integrated open-cycle OTEC systems have not yet been tested in the marine environment, but research was conducted using laboratory data to predict performance and cost. Studies indicate that an open-cycle plant for producing electricity may soon be feasible. The on-shore design uses efficient direct-contact condensers and an array of small power modules to eliminate the need for a single large turbine. An open-cycle system with this design may achieve a cost goal of $7,200/$kW_e$, making OTEC systems competitive in tropical island markets.[28] OTEC may be even more cost-effective if electricity costs can be offset by the sale of desalinated water. This would be especially true in places like the Virgin Islands, where fresh water costs $3/$m^3$.

Analysis also identified critical issues in the design of open-cycle systems. Factors most likely to influence cost and performance include the choice of plant location, the design of seawater pipes and vacuum containment structures, the efficiency of heat exchangers and exhaust systems, and the performance of turbines. In addition, the production of desalinated water from prototypical surface condensers must be tested under OTEC conditions. Until these issues are more fully investigated and resolved, a more accurate cost estimate of an open-cycle system will be difficult to make.

Current Activities in OTEC

Current efforts in the United States are focused on the NPPE to be conducted at the STF in about 1992. The objective of this experiment is to assess the technical feasibility of producing net power in an open-cycle OTEC system. This experiment will include components such as a spout evaporator, a low-pressure steam turbine, and a two-stage direct-contact condenser.

Work is under way to prepare for this experiment. A preliminary experiment is now in progress using the HMTSTA located at the STF. The experiment is proving the performance of a spout evaporator and surface condenser under prototypical conditions and, for the first time in the DOE program, is producing desalinated water in the process.[17]

In addition, computer models were developed for the various open-cycle OTEC subsystems, including the evaporator, surface and direct-contact condensers, and deaerators. Also being developed is a thermoeconomic model for shore-based, open-cycle OTEC plants. The model will help identify optimum configurations for commercial and experimental open-cycle systems. This model assumes a modular plant, with each module using a pair of the low-pressure stage rotors from a conventional multistage steam turbine to produce about 3-MW_e net output. System cost versus plant configuration was computed with this model; economies of scale are achieved at about 10 MW_e with a cost of about $5,000/$kW_e$ when the cold-water pipe is 2250 m long.[28]

Chapter 3

The Seawater System

The seawater system for an OTEC plant consists of warm- and cold-water intake pipes, discharge pipes, and pumps. These components must be large and durable enough to handle the high volume of water that a commercial OTEC plant requires. Two distinct and unique approaches to meeting these requirements were developed. For large plants (more than 40 MW_e capacity), concepts for suspended seawater systems for floating platforms were developed and evaluated. OTEC-1 showed that components with these characteristics will work. For smaller plants, particularly those located where the cold-water resource is close to shore, bottom-mounted system and installation designs have been completed.[13] Researchers completed a preliminary design for a 40-MW_e shore-based facility and are developing improved components and installation techniques for shore-based plants.

Suspended Seawater Systems

Large OTEC plants require huge amounts of seawater circulating through them. For instance, a 100 MW_e plant would operate with 300 m^3/s of cold water flow and 400 m^3/s of warm water flow. This would require pipes 15 - 18 m in diameter. Studies on plants of this size have focused on using floating platforms, either grazing or moored. Primary issues associated with the seawater systems for such plants relate to material choices, construction methods, pipe deployment and installation, and the design of the interface between the platform and the pipe. Several materials have been evaluated, including galvanized steel, concrete, polyethylene, and fiberglass-reinforced plastic. Many show promise of being flexible enough for deployment and durable enough for continuous operation.[29] The suitability of high-density polyethylene for the suspended installation was demonstrated on a floating platform.[11]

Installation techniques have also been investigated. Proven techniques for joining a pipe to a floating platform include "flip and float," in which a fully assembled pipe is towed to the site, upended, and attached through a flexible collar or gimballed to the platform. This method was used to deploy the suspended pipes of Mini-OTEC and OTEC-1.

The OTEC-1 facility received its cold-water supply from three polyethylene pipes that were banded and strapped together. The pipes were fabricated by DuPont Canada, Inc., in sections measuring 1.2 m in diameter and 24.4 m in length; this diameter was the largest that could be extruded in the company's Huntsville, Ontario, plant. Fabricated sections were loaded onto railroad cars and transported from Ontario to Vancouver Harbor, from where they were shipped by barge to Kawaihae Harbor on the island of Hawaii. There, the pipe sections were fused into three pipes, each 640 m long. As shown in Figure 3.1, the pipes, bundled into a triangular shape, were strapped together and fitted with a connecting collar at one end. Two small tugboats were used to tow the structure 32 km off shore where it was upended and attached to the OTEC-1 vessel. This pipe successfully provided cold water throughout the test period despite heavy seas and strong currents.

The platform/pipe interface for floating OTEC systems was investigated by mathematical modeling of the structural dynamics of the platform, pipe, and mooring lines combination. This research, which culminated in a ⅓-scale (of a 40-MW_e prototype plant) suspended pipe experiment conducted in Hawaii, established the design, construction, and installation methods necessary for using large, suspended pipes.[30] However, some uncertainty remains about the long-term materials properties (if composite plastic materials are used), maintenance and repair procedures, and the design and performance of the mooring systems. This uncertainty and the fact that the near-term market will probably opt for smaller OTEC plants have led to the more recent research emphasis on bottom-mounted pipe systems.

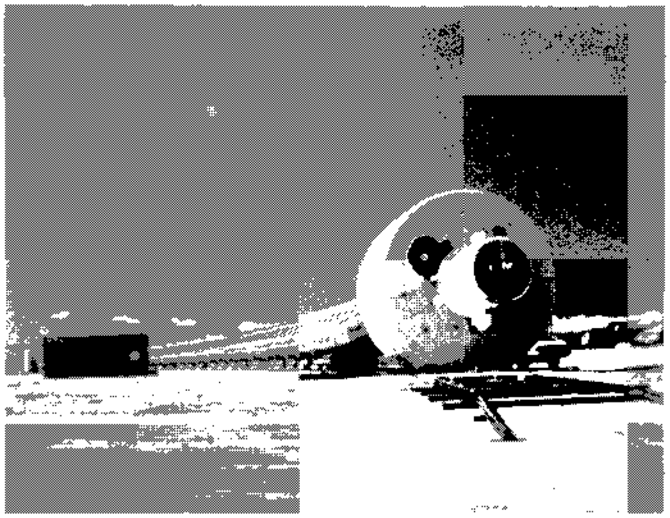


Figure 3.1 Bundled OTEC-1 cold seawater pipes with a gimballed collar *(Courtesy of Global Marine Drilling Company)*

Bottom-Mounted Seawater Systems

Commercial land- or shelf-based OTEC plants will require intake and discharge pipes[28] that can handle seawater flow rates of 20–60 m^3/s. Pipes must withstand the forces of waves and currents, as well as corrosion and biofouling over a projected plant lifetime of 30 years. These requirements are most challenging for cold-water intake pipes that will be up to 5 km long, descend to a depth of more than 600 m, and have diameters of up to 5 m. The seawater systems of land-based plants have special requirements for the discharge pipe and the surf zone transition for all the pipes of the system. Installation techniques strongly influence the choice of pipe materials.

The OET Program has looked at two installation approaches. In the first, pipes would be installed section by section and then joined after they were in place on the ocean bottom. This installation method can use any pipe material; a fiberglass composite was used in the "proof of concept" plant design at Kahe Point and in a down-the-slope experimental pipe 24 m long and 2.4 m in diameter at NELH. Results of the NELH experiment showed that reinforced plastic pipes can withstand the stresses of installation and the ensuing wave and current action. Joining many segments, however, is a time-consuming process vulnerable to unfavorable weather changes and requires developing a pipe-joining process that could be carried out in deep seawater.[13] A second approach uses a long, preassembled pipe that is towed outward from shore to a predetermined position, weighted, and sunk in place. This method was successful at the STF in Hawaii, where the near-shore segment was chained to rock bolts on the sea bottom and the offshore section remained floating in a buoyant suspended arc (inverse catenary) held at the intake by a large anchor.[31]

The Japanese are also developing different methods for installing cold-water pipes. A Japanese team recently installed a polyethylene pipe with a diameter of 0.5 m and a length of 2400 m. The pipe was launched from a specially built platform and towed to sea, a process that required 59 hours of good weather. Pressure buoys kept the pipe floating just above the sea bed as the pipe was towed. The buoys were disconnected automatically by a timed chemical reaction that caused the supporting rods between the pipe and the buoys to fail at a prescribed time. Heavy steel bands caused the pipe to sink to its permanent location on the sea bed.[32]

Figure 3.2 Deployment of the 1-m cold-water pipe at the Natural Energy Laboratory of Hawaii *(Courtesy of R.M. Towill Corporation)*

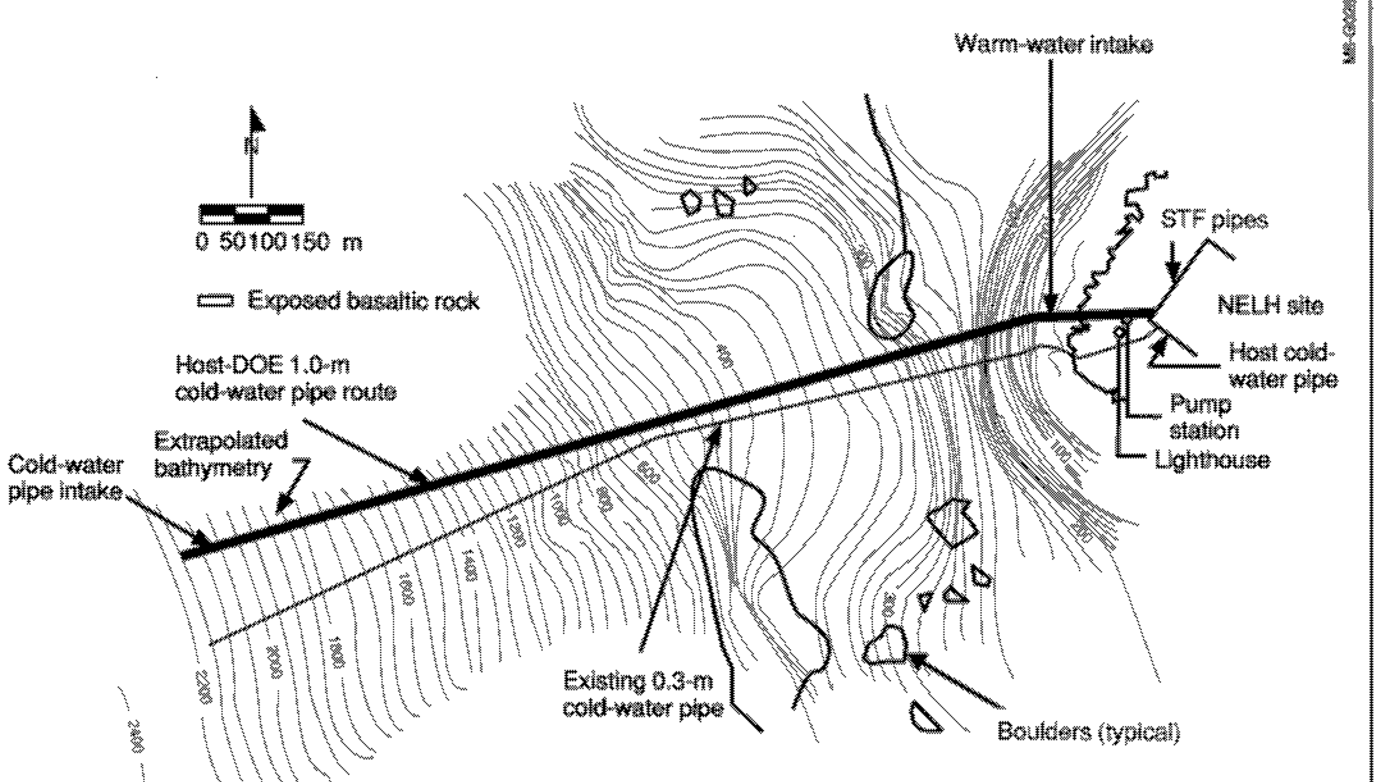
Several seawater pipes using the single, long pipe construction were successfully installed at NELH. The original construction for cold-water delivery used an inverted catenary, polyethylene pipe measuring 0.3 m in diameter that was slightly buoyant. It was deployed to a water depth of approximately 670 m and has survived for many years with little damage or biofouling. This pipe is small, however, compared with those required for commercial-scale OTEC plants.[33] More recently, a pipe measuring 1 m in diameter and 2060 m long was deployed to a water depth of 670 m to provide an augmented cold-water supply for the STF[31] (see Figure 3.2). These pipes were installed in the inverse catenary configuration shown in Figure 3.3. The installation can be described in terms of three zones along the pipe's length. Near the shore (to a water depth of about 15 m) the pipe is placed in a trench to protect it from wave and current forces. (An alternative to the trench might be a concrete duct placed on the sea bed surface.) The second zone extends from where the pipe emerges from the trench to a depth of about 100 m. Chains to rock bolts at the shoreward end and concrete anchors strapped to this pipe section at about 3–6-m intervals are adequate to secure the pipe. In the third zone, the pipe takes off from a convenient anchor point into an inverse catenary arc and bridges the rest of the sea bed to the end point anchor at the cold-water inlet. The clear advantages of this approach are decreased deployment time and freedom from sea bed path constraints.

Polyethylene was used in both installations because it is buoyant and has the inherent flexibility needed to accommodate the extent of deflection required during the "controlled sink" deployment process. These techniques and materials probably can be extended to a pipe diameter of up to 1.3 m using currently available piping materials and handling equipment.

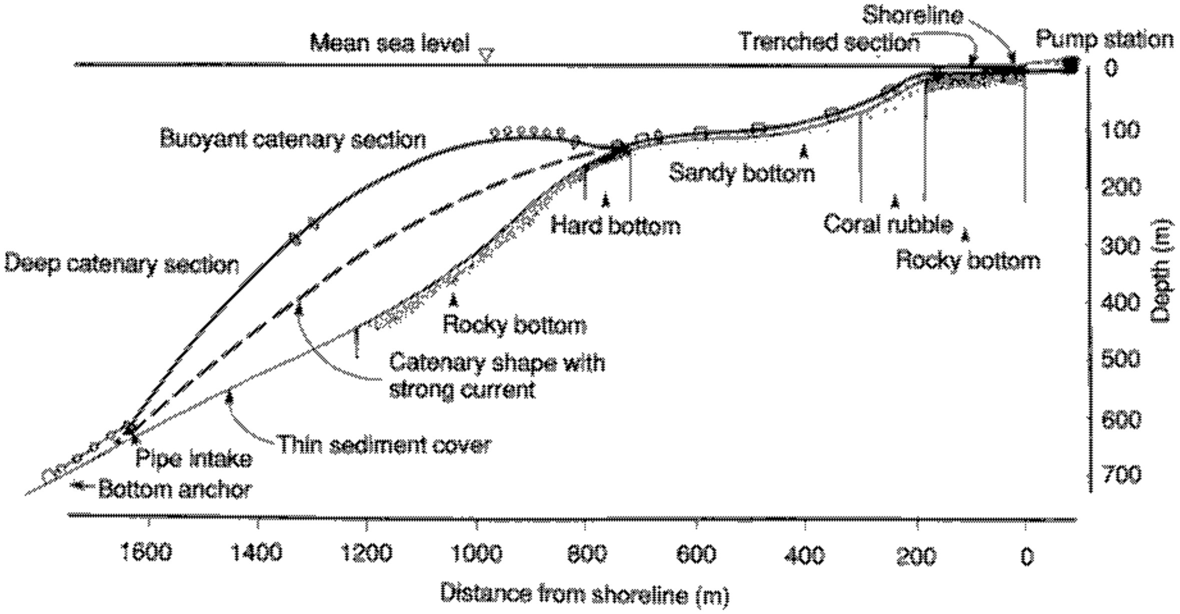
The near-the-bottom deployment developed by the Japanese should have limitations similar to those of the controlled sink process, although it may accommodate slightly larger and stiffer pipes.

Discharge Pipe

Performance and environmental considerations dictate the requirements of the seawater discharge pipe from an OTEC plant. Because both of the warm- and cold-water streams must be discharged, the designer can choose either two discharge pipes or a single, mixed-discharge pipe. In either case, the pipe must be sized to minimize pressure losses and located to prevent reingestion of the effluent into the



a. Plan view



b. Profile view

Figure 3.3 Plan and profile views of the 1-m cold seawater supply system at the Natural Energy Laboratory of Hawaii[31] warm-water inlet. The density of the effluent should match the density (and temperature) of the environment into which it is discharged so that any differences are quickly mitigated and the effects on the thermal resource and the environment are minimized. This calls for a pipe that extends into the thermocline, a depth of about 100 m for mixed discharge in Hawaiin waters.[34]

The combined discharge from a floating plant requires an additional pipe larger in diameter than either intake pipe, extending through the mixed-layer depth. Land-based or shelf-mounted plants have the same requirement except that the competition for potential pipe routes increases the possibility for interference between the pipes during installation or operation. Routing the discharge water into a well or a trench is an alternative that can be considered only for very small plants and where environmental considerations permit. In the latest seawater system constructed at NELH, the effluent is discharged into a trench from which it percolates to the surrounding ocean through fissures or pores in the ground. Such a discharge system will be continuously monitored to evaluate its effects on the environment, according to the Cooperative Environmental Monitoring Program.[35]

Pumps

Submersible and surface-mounted pumps of the capacity required in a 10-MW$_e$ OTEC plant (approximately 19 m^3/s) are commercially available and can be expected to operate reliably at high efficiency (85%–90%) for the life of the plant. Surface-mounted pumps are available in sizes up to approximately 158 m^3/s, which probably is the practical limit for pump size. Seawater operation of these pumps is well established in the offshore oil and power plant industries. Special alloys are required for all wet parts, however, which can more than double the cost compared with cast-iron pumps of identical design. Industry sources project a 40-year life with maintenance cycles of up to 10 years as distinct possibilities for OTEC pumps.[36]

The STF draws cold water from the original 0.3-m cold-water pipe with three offshore pumps having a total capacity of 0.07 m^3/s. To achieve the proper net positive suction head, these pumps had to be installed below sea level. Initial designs called for the cold-water pumps to be housed on shore, but the cost of trenching pipes to the pumphouse was prohibitive. Instead, submersible pumps were built to specification and installed at a water depth of about 10 m.[37]

This underwater pumping system proved difficult to maintain and repair. Primary problems were with pump failure due to corrosion of parts that did not match specifications and due to failures in electrical connections. Parts exposed to seawater should be constructed of 316 stainless steel, or an equivalent alloy, to prevent corrosion and contamination of the water supply; specifications must be conservatively prepared and carefully monitored. Special techniques for maintaining the pumps during heavy seas had to be developed. In contrast, the STF's original four onshore warm-water pumps for this seawater system performed well; few problems were experienced in either performance or repair. Based on this experience, all pumps for the new 1-m-diameter seawater system were installed in an onshore pumphouse[31] and protected against galvanic corrosion with an impressed current system. Current design philosophy calls for designing near-shore components conservatively, including selecting durable and accessible electrical cables and conduits. The discrepancy between industry projections and program field experience pointed out the importance of exact specification and coordination with suppliers.

Current Activities in Seawater Systems

The current state of the art in cold-water pipes for shore- or bottom-mounted OTEC plants is represented by the 1-m-diameter, 2060-m-long polyethylene pipe installed at NELH in 1987. Design, construction, and installation of this pipe were joint efforts of the state of Hawaii, DOE, and the Pacific International Center for High Technology Research (PICHTR). Fabrication of the pipe at Kawaihae Harbor took about 25 days, and deployment took about a week. The cold- and warm-water sections of the seawater supply system can provide volume flow rates of 0.84 and 0.60 m^3/s, respectively.[31]

Another recent activity sponsored by DOE and conducted by PICHTR was a workshop on bottom-mounted cold water pipes held in Hawaii in 1988. This workshop's major objectives were to identify and characterize state-of-the-art near-shore seawater pipe construction techniques and identify innovative concepts for constructing and installing deep-water portions of an OTEC cold-water pipe. For OTEC systems in the 5–15-MW$_e$ power range, the state-of-the-art approach for near-shore areas is to trench and bury. The cost of this construction is very site-specific, although major sewer outfall installations have demonstrated its technical feasibility. Concepts considered in the past for the deep section of the cold-water pipe include drilling and tunneling, pendant-supported pipes, and buoyant catenary designs. Among these, bottom-mounting and anchoring, and perhaps drilling and tunneling, are options with greater risks. All need further study before being applied to large pipe sizes. The pendant-supported pipes and the buoyant catenary designs, in all probability, would need to operate under pressure with the supply pump located at the pipe inlet, allowing the consideration of thin-walled, reinforced, elastomer pipe that can reduce material and installation costs.[38]

With the OET Program's cold-water pipe needs satisfied for the next several years by the recent and ongoing construction at NELH, current activity in the program is limited to evaluating innovative concepts for large pipes and planning for future activities.

Chapter 4

Complementary OTEC Products

As mentioned earlier, an OTEC plant can produce valuable complementary products such as desalinated water in addition to generating power. The cold seawater can be used for culturing marine life and for refrigeration and air-conditioning. These potentially synergistic activities may make OTEC systems attractive to industry and island communities even if the price of oil remains low. Some of the products and services that could be produced from an integrated OTEC system are shown in Figure 4.1.

Desalinated Water

Desalinated water can be produced in open- or hybrid-cycle plants using surface condensers. In a surface condenser, the spent steam is condensed by indirect contact with the cold seawater. This condensate is relatively free of impurities and can be collected and sold to local communities where natural fresh-water supplies for agriculture or drinking are limited.

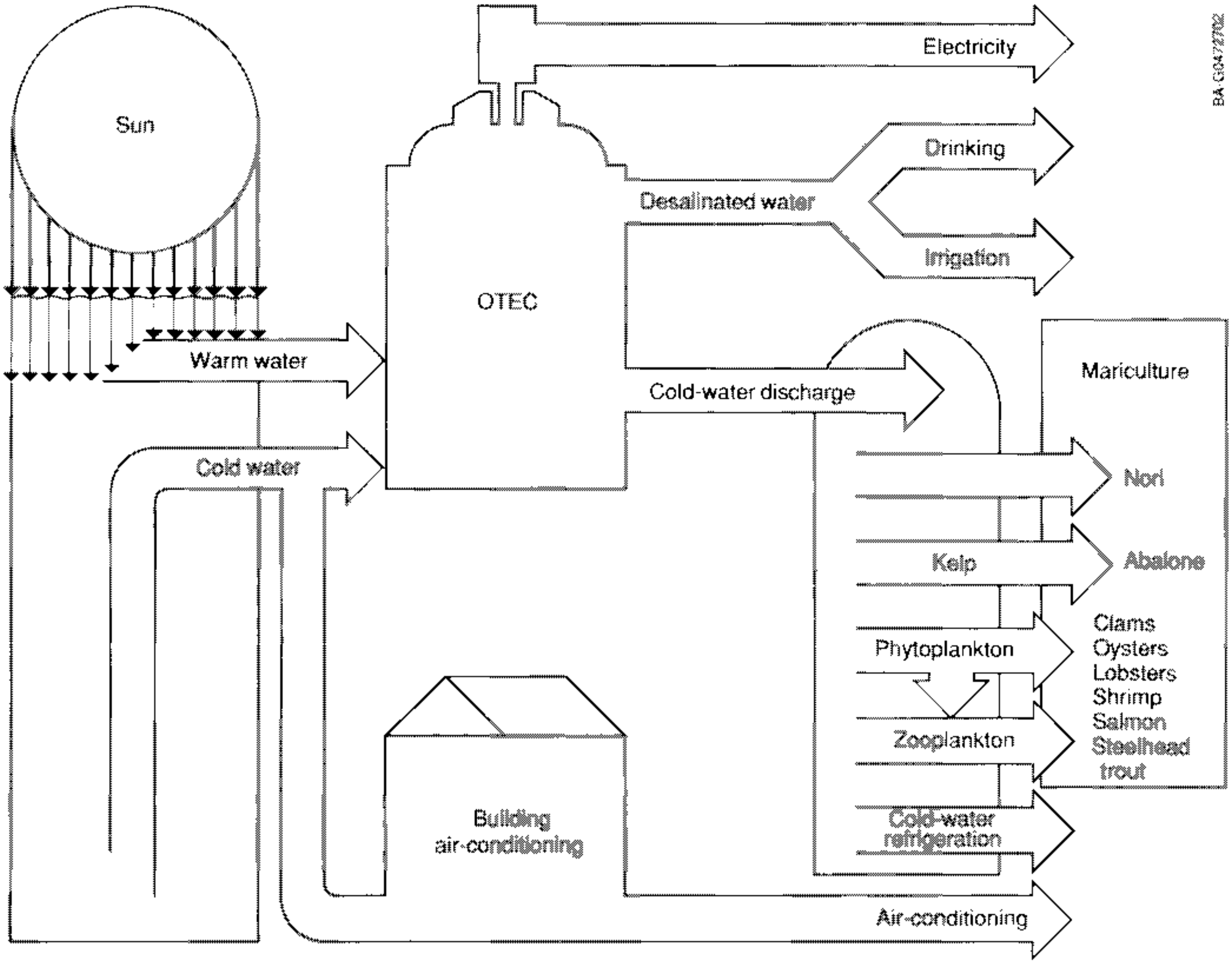


Figure 4.1 A multiple product/application-integrated OTEC plant

Figure 4.2 Ocean Farms of Hawaii's mariculture tanks *(Courtesy of NELH)*

System analysis indicates that a 2-MW_e net plant could produce about 4320 m^3 of desalinated water a day.[28]

The large surface condensers required to condense the entire steam flow increase the size and cost of an open-cycle plant. A surface condenser can be used to recover part of the steam in the cycle and to reduce the overall size of the heat exchangers; the rest of the steam can be passed through the less costly and more efficient direct-contact condenser stages. A second-stage direct-contact condenser concentrates the noncondensable gases and reduces the size of the vacuum exhaust system, thereby increasing the plant's net power.

A way to produce large quantities of desalinated water without incurring the cost of an open-cycle turbine is with a hybrid system in which desalinated water is produced by vacuum flash distillation and power is produced by a closed-cycle loop. Other schemes that use discharge waters from OTEC systems to produce desalinated water have also been considered.

Deep-Water-Supported Mariculture

Deep-drawn seawater from an OTEC plant is cold, rich in nutrients, relatively free of pathogens, and available in large quantity. It is an excellent medium for growing phytoplankton and microalgae, which in turn support a variety of commercially valuable fish and shellfish. An OTEC plant can be part of a polyculture operation that combines the production of protein and energy. A seaweed used to wrap sushi (nori) was successfully grown at accelerated rates in NELH experiments. Using phytoplankton and kelp, researchers at NELH have grown salmon, trout, northern lobsters, oysters, giant clams, and abalone with good to exceptional results.[39] Two plastic-lined steel kelp tanks at NELH (Figure 4.2) support oyster, salmon, and abalone production at the Ocean Farms of Hawaii. Several other businesses now use the facility's cold-water supply for commercial projects.

The large, constant flow of water pumped from an OTEC plant will reduce disease and contamination in the ponds; marine life, therefore, can be grown in high density. In addition, deep-drawn cold water can be mixed with warm surface water, allowing local communities to culture a broad variety of species. Such integration of operations would mitigate the large seawater pumping cost to mariculture and increase the revenue for the OTEC plant.

Mariculture facilities probably will be designed for land-based or near-shore plants rather than for offshore OTEC plants. At land-based or near-shore facilities, cold water can be pumped into tanks or lagoons where environmental conditions can be controlled more readily.

Refrigeration and Air-Conditioning

The availability of 6°C cold seawater creates the opportunity to provide large amounts of cooling to operations related or close to the plant. Salmon, lobster, abalone, trout, oysters, and clams are not indigenous to tropical waters, but they can be raised in pools created by OTEC-pumped water to extend the variety of seafood products available in those markets. Likewise, the low-cost refrigeration available from cold seawater can be used to upgrade or maintain the quality of the indigenous fish, which tend to deteriorate quickly in the warm tropical regions. Experiments were conducted successfully on growing fruits and vegetables normally associated with moderate climates, such as lettuce and strawberries. They are grown in gardens cooled and irrigated by a drip system using the fresh water that condenses on the external surfaces of the cold-water pipes.

The cold seawater delivered to an OTEC plant can be used in chilled-water coils to provide building space air-conditioning. It is estimated that a 0.3-m-diameter pipe can deliver 0.08 m^3/s of water. If 6°C water can be received from such a pipe, it could provide sufficient air-conditioning to a large building so that if it operates 8000 h/yr and local electricity sells for 5¢–10¢/kWh, then $200,000–$400,000 could be saved annually.[40]

Current Activities in Complementary Products

Mariculture experiments continue at NELH, where the cold-water pipes provide seawater for research in both OTEC technology and its associated applications. Additional water is being provided at the Hawaii Ocean Science and Technology Park, adjacent to NELH, to support industry in developing products and markets associated with cold seawater. Two commercial mariculture ventures are under way there, and others are in the early stages of development. Ocean Farms of Hawaii uses cold seawater to grow 4,500–23,000 kg of premium abalone each year. Another company, Cyanotech, uses warm seawater to culture several species of microalgae that are sold as protein-rich food supplements, pharmaceuticals, and food coloring.

Other small projects are being carried out on a fragmented basis around the world to evaluate special non-power-producing applications for cold seawater. These efforts are not necessarily tied to OTEC commercialization; however, they may offer the opportunity to generate multiple products and supplemental income from an OTEC plant in specialized applications until OTEC systems can deliver electricity and water to island markets at competitive prices.[39]

Chapter 5

Environmental Issues

The DOE OET Program has funded research to improve our understanding of OTEC interactions with marine ecosystems, adjoining coastlines, and the atmosphere and to identify approaches to lessen any potential adverse interactions. These studies have uncovered no insurmountable environmental obstacles to OTEC deployment; in fact, current evidence suggests that most environmental effects will be minimal compared with those associated with conventional power systems. Careful design and siting, strict operating procedures, and well-trained personnel will produce OTEC systems that are environmentally acceptable sources of power.

Marine Ecosystem Interactions

Like any offshore or shoreline project, commercial OTEC facilities will affect the marine environment. Varying degrees of the potential effects shown in Figure 5.1 are expected from an OTEC plant.[41] Construction activities may temporarily disrupt the sea bed, destroying habitats and decreasing subsurface visibility. Platforms and marine subsystems may attract fish and other marine species; attempts to reduce biofouling may increase the level of toxic substances. Intake pipes can draw marine organisms through the plant and move large amounts of nutrient-rich water up from the depths. However, OTEC systems can be designed and located to minimize their potential effects on the environment.

The construction of land-based or shelf-mounted OTEC plants can disturb the sea bed. Deployment of moorings, cables, pipes, piles, and anchors may churn up the bottom and increase the number of particles suspended in the water. This type of disturbance can affect areas of special ecological importance, such as coral reefs, seagrass beds,

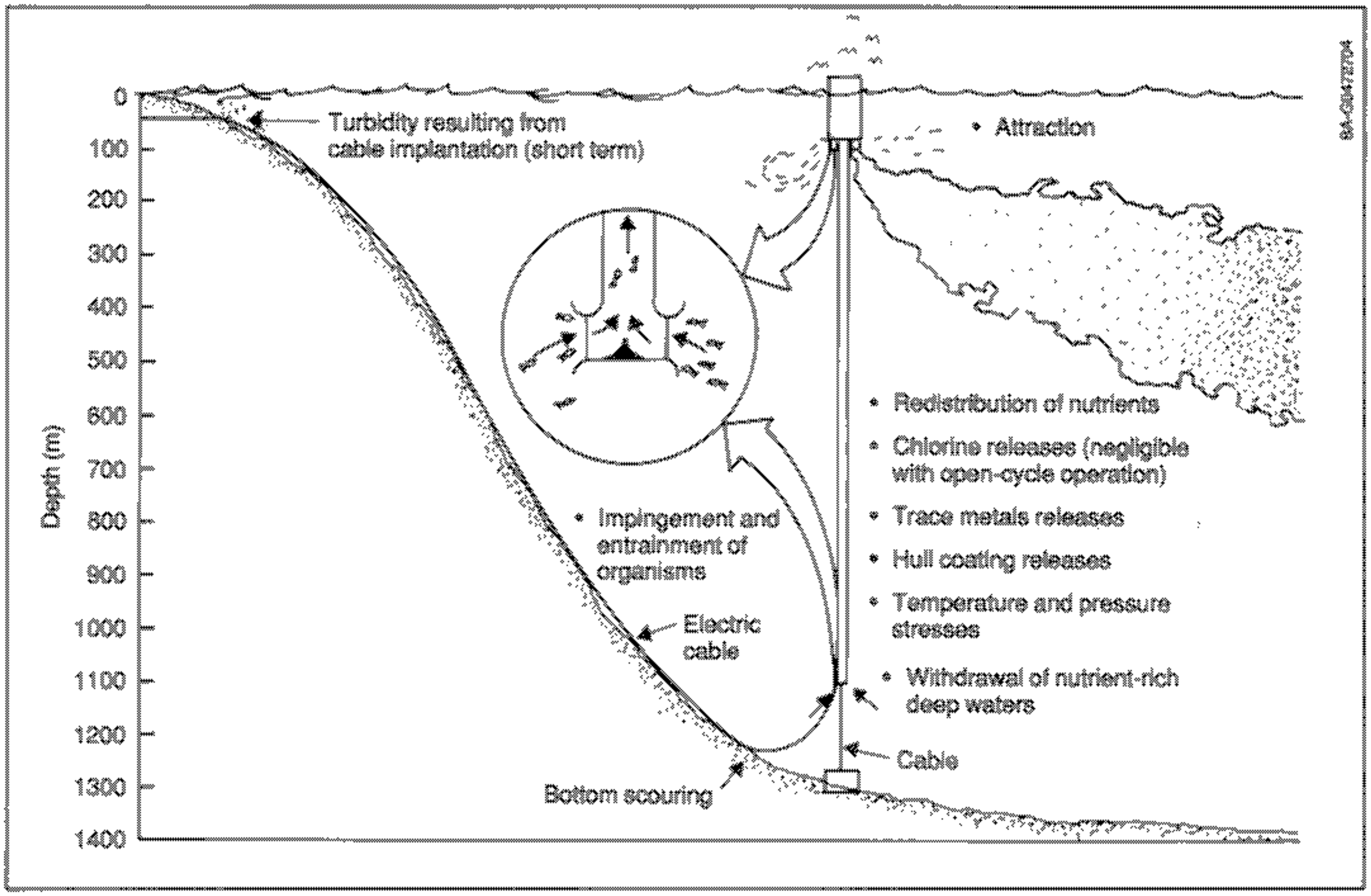


Figure 5.1 Potential environmental effects of pilot-plant operation[41]

spawning grounds, and commercial fisheries. Short-term disruption of most of these habitats is often reversible, as shown by experience with offshore oil rig construction. OTEC developers can minimize disruption by locating plants away from critical habitats. Where necessary, cables and pipes can be routed through natural breaks in near-shore reefs.

An offshore OTEC system may affect marine organisms by providing an attractive artificial reef as well as night illumination. Based on studies of existing power plants and artificial reefs, researchers expect OTEC platforms to attract about twice as much life as would normally be present in the undisturbed marine environment. Sedentary organisms such as barnacles, though, can cause considerable damage to marine structures. Free-swimming organisms can either be trapped on warm-water intake screens (impinged) or carried through the system (entrained). The effect of impingement and entrainment can be minimized by locating OTEC plants away from the spawning grounds of commercially or ecologically valuable organisms. Systems can be designed for horizontal intake at a speed of less than 1 m/s so that large, free-swimming marine organisms can escape the inward flow.

Extensive damage to marine structures can occur as both plants and larvae find new locations for attachment and growth. Inside the OTEC system, this attachment can be prevented by periodic, controlled release of chlorine or other biocides. On outside surfaces, colonization can be forestalled by using toxic coatings. However, biocides and slowly released toxins may affect life downstream from the plant and may accumulate in the marine food chain. The extent of such an environmental impact is not yet fully understood, but researchers continue to assess the effects of using biocides and to investigate nonchemical alternatives. These alternatives include using coatings that resist attachment, ultraviolet radiation, and mechanical scrubbing.

OTEC plants discharge large quantities of ocean water and potentially perturb natural thermal and salinity gradients and levels of dissolved gases, nutrients, trace metals, carbonates, and turbidity. If cold- and warm-water streams are mixed and discharged at the surface, the density of OTEC plant discharges will be different from that of the surrounding water. Behavior of the discharge plume will respond to initial discharge momentum and to buoyancy forces that result from initial density differences. Within several hundred meters of the discharge point, the plume will be diluted by ambient ocean water, sink (or rise) to reach an equilibrium level, and lose velocity until the difference between its velocity and ambient current velocity is small. OTEC plants can be designed to stabilize the discharge plume below the mixed layer to protect the thermal resource and to minimize potential environmental effects.

An environmental impact of a more serious nature could occur if ammonia, Freon®, or some other environmentally hazardous working fluid accidentally spilled from a closed-cycle OTEC plant. The effect of ammonia on marine ecosystems would depend on the rate of release and the nature of nearby sea life. Small quantities of ammonia probably would stimulate plant growth downstream. A large ammonia spill would be toxic; for example, a 40-MW_e plant could spill enough ammonia to destroy marine organisms over an area as large as 4 km^2. This possibility can be minimized by designing the plant for safety and careful operation and employing well-trained, attentive personnel.[42]

Adjoining Coastline Interactions

The effect of OTEC plant construction on the coastline will be comparable to that of other major building projects. For shelf-mounted or land-based OTEC facilities, site preparation and plant construction could disrupt terrestrial, tidal zone, and near-shore habitats. Noise, traffic, and dust levels will increase. Blasting may be necessary, depending on the geology of the area and the method of pipe placement. The extent of these effects will vary, but careful siting and well-planned construction should minimize disturbance of the coastline environment.

Atmospheric Interactions

OTEC facilities release no additional heat and significantly less carbon dioxide than comparably sized conventional fossil-fueled power plants. These advantages may become increasingly important in the future if predictions concerning global climate change are correct and power plants are required to reduce carbon dioxide production significantly.

Changes in the ocean's surface temperature could lead to dramatic changes in continental weather patterns; however, the size and number of OTEC plants that can be projected in an area for the foreseeable future preclude a significant contribution to the effect. For performance reasons (to avoid reingestion of cool discharge water), this discharge will be directed deep into the ocean where it would have minimal influence on surface temperature. Researchers predict that the small amount of water brought to the surface by local mixing would not decrease temperature enough to affect climate.

It has been projected that circulating and warming large amounts of deep ocean water in any OTEC plant operation could result in outgassing of dissolved carbon dioxide if the discharge is exposed to the atmosphere for sufficient periods. Recently completed experiments indicate that the immediate carbon dioxide release from an open-cycle OTEC plant would be 15 to 25 times smaller than the emission from a comparably sized fossil-fueled electric power plant.[43] The variability of natural outgassing in tropical oceans will greatly exceed any projected OTEC release.[41] The potential for long-term release of carbon dioxide could be slightly higher if the discharge water is used for mariculture or other secondary operations. Most of the potential long-term and immediate releases can be avoided completely by reinjecting any absorbed gas into the seawater discharge, by introducing that discharge below the surface mixed layer of the ocean, or by combining these methods.

Current Activities in Environmental Assessment

The operating permit requirements of the various county, state, and federal agencies with oversight at NELH call for an environmental monitoring program that will help protect the unique resources in the Keahole Point area. To evaluate long-term effects on the environment, results of the monitoring will be compared with a baseline of groundwater and offshore water quality and offshore biota that is being established at NELH. The OET Program is supporting a state effort that consists of reviewing archival data and collecting site data to establish benchmark conditions at Keahole Point, which is likely to be the area for OTEC development in the near future.[35] The program is also providing technical and fiscal support for managing the environmental quality at the site.

Chapter 6

The Future of OTEC

The DOE OET Program has proven the feasibility of closed-cycle OTEC and has brought it to the threshold of commercialization. Today, the program continues to advance OTEC technology by funding research in surface condensers, biofouling, corrosion, and open-cycle OTEC systems. The knowledge gained from this research may allow industry to engineer the 2–15 MW_e plant envisioned for entry into tropical island markets. In addition, the recent "first" production of desalinated water at the STF using open-cycle OTEC technology has stimulated considerable interest in the process.

The major objective of the ongoing DOE program is to develop a data base and verify design codes while experimentally demonstrating the technical feasibility of producing a significant amount of net electric power in an open-cycle OTEC system. The NPPE, shown in Figure 6.1,

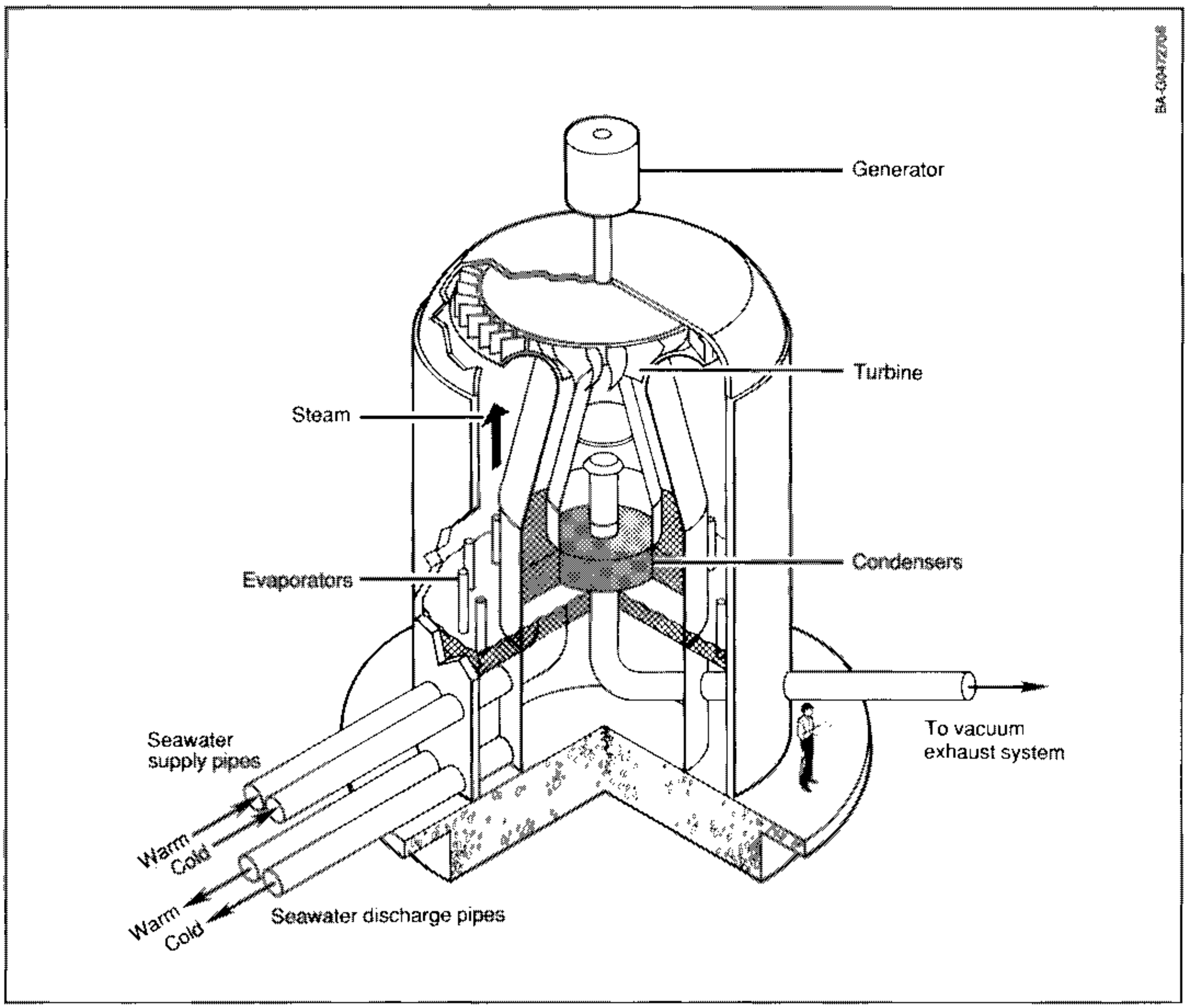


Figure 6.1 Artist's rendering of the net power-producing experiment

will be developed from the technology and hardware currently being tested in the HMTSTA at NELH. It will use 0.4 m^3/s of cold seawater and 0.6 m^3/s of warm seawater drawn from the seawater systems recently installed at NELH. The experiment will use a low-pressure steam turbine that SERI, PICHTR, and industry are designing and a high-efficiency gas compressor that SERI is developing. The experiment's turbine/generator is expected to deliver nominally 165 kW$_e$ (gross) at its design point and to produce 40 kW$_e$ of net power.[7] As the plant size increases, a smaller portion of gross power will be needed to operate the plant. Researchers therefore project that a commercial-sized power module based on current technology could produce 2.4 MW$_e$ and deliver 1.75 MW$_e$ to a utility company or community power distribution system.[28]

Several nations besides the United States are interested in developing full-scale OTEC plants.[44] Japan has completed a design study of a 10-MW$_e$ (net) floating facility to be located in the Sea of Okinawa.[45] This was one of a series of activities that included constructing experimental plants in Nauru[4] and Tokunoshima[32] and completing design studies for other locations in the western Pacific. This research continues and is focused on the possibility of constructing small, closed-cycle plants in the small, oil-dependent islands of the Pacific. The Taiwan Power Company completed studies on the feasibility of placing 50-MW$_e$ plants on the eastern coast of that country. The company projected that such plants will become competitive with oil-fired and coal-fired plants in the mid-1990s. It is now planning a pilot plant that would precede commercialization in that time frame.[46]

GEC-Marconi, a British firm working with Alcan International of Canada, reported preliminary design work on a small, land-based closed-cycle OTEC plant that it plans to build and operate at Keahole Point in Hawaii.[47] This plant, as proposed, will provide the technical basis for scaling up to commercial-sized 10-MW$_e$ plants.

A French government research and development group, IFREMER, joined seven French companies in considering developing a 5–20-MW$_e$ open-cycle plant to be located in Tahiti. The Netherlands, in cooperation with several Indonesian companies, completed a feasibility study for a 100-kW$_e$ closed-cycle plant at a South Pacific site. The governments of Sweden, Norway, and Jamaica have been cooperating with private companies since 1980 in designing a 1-MW$_e$ closed-cycle plant to be located near Kingston, Jamaica. The latter three projects[44] are inactive because of the current low cost of oil. Although interest in OTEC remains high, the prospects for its commercialization are held back by relatively plentiful and inexpensive oil supplies. There is an increasing awareness that the multiple product potential of OTEC plants to provide power, water, food, and refrigeration to remote island communities in an integrated system will stimulate their economic development.[17] Such a development appears attractive in the short term.

References

1. d'Arsonval, A., "Utilization des forces naturelles. Avenir de l'electricite," *Revue Scientifique*, Vol. 17, 1881, pp. 370–372.

2. Claude, G., "Power from the Tropical Seas," *Mechanical Engineering*, Vol. 52, No. 12, 1930, pp. 1039–1044.

3. Massart, G.L., "The Tribulations of Trying to Harness Thermal Power," *Marine Technology Society Journal*, Vol. 8, No. 9, Oct/Nov 1974.

4. Titsui, T., F. Ito, Y. Seya, and Y. Nakamoto, "Outline of the 100-kW OTEC Plant in the Republic of Nauru," *IEEE Transactions on Power Apparatus and Systems*, Vol. PAS 102, No. 9, September 1983.

5. U.S. Department of Energy, *Federal Ocean Energy Technology Program Multi-Year Program Plan: FY 1985–1989*, DOE/CH10093-100, Washington, DC: U.S. Department of Energy, 1985, 37 pp.

6. Rogers, L., "The U.S. Department of Energy Ocean Energy Technology Research Program," *Proceedings, International Renewable Energy Conference*, Honolulu, Hawaii, September 1988, pp. 59–65.

7. Shelpuk, B., "A 165-kW Open Cycle OTEC Experiment," presented at the 12th Annual Intersociety Energy Conversion Engineering Conference, Miami Beach, FL, August 1985; also SERI/TP-251-2725, Golden, CO.

8. Link, H., and B. Parsons, "Potential of Proposed Open-Cycle OTEC: Experiments to Achieve Net Power," *Marine Technology Society/IEEE Oceans '86 Conference Record*, Washington, DC, September 23–25, 1986, New York: The Institute of Electrical and Electronic Engineers, Inc., pp. 207–212.

9. Link, H., "Operational Experience of the OC-OTEC Experiments at NELH," *Proceedings, ASME Annual Solar Energy Division Conference*, San Diego, CA, April 2–5, 1989, New York: American Society of Mechanical Engineers, pp. 313–321; also SERI/TP-253-3480, Golden, CO.

10. Owens, W.L., and L.C. Trimble, "Mini-OTEC Operational Results," *ASME Journal of Solar Energy Engineering*, Vol. 103, 1981, pp. 233–240.

11. Lorenz, J.J., D. Yung, P.A. Howard, C.B. Panchal, and F.W. Pucher, "OTEC-1 Heat Exchange Test Results," *Proceedings, Eighth Ocean Energy Conference*, Washington, DC, June 1981, Washington, DC: U.S. Department of Energy, pp. 977–990.

12. Cohen, R., "Energy from the Ocean," *Philosophical Transactions of the Royal Society of London: Series A: Mathematical and Physical Sciences*, Vol. 307, No. 1499, 1982, pp. 405–437.

13. Ocean Thermal Corporation, *40-MW$_e$ OTEC Power Plant Final Technical Report*, 4 volumes, New York: Ocean Thermal Corporation, 1984.

14. Thomas, A., and D.L. Hillis, "Biofouling and Corrosion Research for Marine Heat Exchangers," *Marine Technology Society/IEEE Oceans '89 Conference Proceedings*, Seattle, WA, September 18–21, 1989.

15. Panchal C., J. Larsen-Basse, and B. Little, "Biofouling Control for Exchangers Using Intermittent Chlorination," *Proceedings, 22nd ASME-AIChE National Heat Transfer Conference*, Niagara Falls, NY, Aug., 1984, New York: American Society of Mechanical Engineers.

16. Bharathan, D., and T. Penney, "Flash Evaporation from Turbulent Water Jets," *ASME Journal of Heat Transfer*, Vol. 106, 1984, pp. 407–415.

17. Rogers, L., and A. Trenka, "An Update on the U.S. Department of Energy Ocean Energy Program," to be presented at the American Society of Civil Engineers International Conference on Ocean Energy Recovery, Honolulu, Hawaii, November 28–30, 1989, New York: ASCE, in press.

18. Bharathan, D., and T. Penney, *Mist Eliminators for Freshwater Production from Open Cycle OTEC Systems*, SERI/TR-252-1991, Golden, CO: Solar Energy Research Institute, 1983, 35 pp.

19. Westinghouse Electric Corporation, *100-MW$_e$ OTEC Alternate Power Systems*, final report to U.S. Department of Energy under contract EG-77-C-05-1473, Vol. 1, 1979.

20. Valenzuela, J.A., T. Jasinski, W.D. Stacey, B.R. Patel, and E.Y. Dolan, *Design and Cost Study of Critical OC-OTEC Plant Components*, SERI/STR-252-3246, Golden, CO: Solar Energy Research Institute, 1988, 197 pp.

21. *Innovative Turbine Concepts for Open-Cycle OTEC*, SERI/TR-253-3549, Golden, CO: Solar Energy Research Institute, in press.

22. Bharathan, D., B.K. Parsons, and J.A. Althof, *Direct-Contact Condensers for Open-Cycle OTEC Applications: Model Validation for Structured Packings Using Fresh Water*, SERI/TR-252-3108, Golden, CO: Solar Energy Research Institute, 1988.

23. Parsons, B.K., D. Bharathan, and J.A. Althof, *Thermodynamic Systems Analysis of Open-Cycle Ocean Thermal Energy Conversion (OTEC)*, SERI/TR-252-2234, Golden, CO: Solar Energy Research Institute, 1985.

24. Panchal, C., and K.J. Bell, "Simultaneous Production of Desalinated Water and Power Using a Hybrid Cycle Plant," *Journal of Solar Energy Engineering*, Vol. 109, 1987, pp. 156–160.

25. Dugger, G.L., L.L. Perini, D. Richards, and F.C. Paddison, "The Potential for a Hybrid Geothermal-Ocean Thermal Energy Conversion (GEOTEC) Power Plant Installation at Adak Island, Alaska," *Proceedings, 18th Intersociety Energy Conversion Engineering Conference, "Energy for the Marketplace,"* Orlando, Florida, August 1983, pp. 355–363.

26. Pacific International Center for High Technology Research/Solar Energy Research Institute Turbine Workshop, Honolulu, Hawaii, December 1986, in press.

27. Francis, E.J. W.H. Avery, and G.L. Dugger, "Comparison of Cost Estimates, Sharing Potentials, Subsidies, and Uses for OTEC Facilities and Plantships," *Proceedings, Seventh Ocean Energy Conference*, Washington, DC, June 1980, Washington, DC: U.S. Department of Energy, Sec. 13.1, pp. 1–8.

28. Block, D., and J. Valenzuela, *Thermoeconomic Optimization of OC-OTEC Electricity and Water Production Plants*, SERI/STR-251-2603, Golden, CO: Solar Energy Research Institute, 1985, 403 pp.

29. Marine Board-National Research Council, *Ocean Engineering for Ocean Thermal Energy Conversion*, Washington, DC: National Academy Press, 1982.

30. Hawaiian Dredging and Construction Co., *OTEC Cold Water Pipe at Sea Test Program, Phase II: Suspended Pipe Test Final Report*, Washington, DC: National Oceanic and Atmospheric Administration, U.S. Department of Commerce, 1982.

31. Lewis, L.F., J. Van Ryzin, and L. Vega, "Steep Slope Seawater Supply Pipeline," *Proceedings, American Society of Civil Engineers 21st International Conference on Coastal Engineering*, 1988, Costa Del Malaga, Spain, New York: ASCE.

32. Iso, S., I. Kondo, Y. Adachi, F. Tamamura, T.S. Chung, K. Yoshida, C.P. Ellinas, T. Huang, H.C. Rhee, and T. Penney, "Installation of OTEC Cold Water Pipe in Tokunoshima by Semi-Floating Type Submarine Method," *Proceedings, Fifth International Offshore Mechanics and Arctic Engineering Symposium*, Tokyo, Japan, April 13–18, 1986, New York: American Society of Mechanical Engineers, pp. 599–605.

33. Daniel, T.H., "New Seawater Delivery Systems at the Natural Energy Laboratory of Hawaii," *Proceedings, 11th Annual Solar Energy Conference*, San Diego, CA, April 1989, pp. 323–330.

34. Harms, V., and A.T. Dengler, Jr., Marine Sciences Group, *Seawater-Discharge Analysis and Effluent-Plume Characteristics for the STF Upgrade Project*, MS6 85-020, Berkeley: University of California, 1985.

35. High Technology Development Corporation, *Hawaiian Ocean Science and Technology Park and Natural Energy Laboratory of Hawaii Cooperative Environmental Monitoring Program*, prepared for the state of Hawaii, unpublished draft, March 1989.

36. Krutzch, W.C., "A State-of-the-Art Look at OTEC Pumping Requirements," *Proceedings, 11th Annual Offshore Technology Conference*, April 30–May 3, 1979, Houston, TX.

37. Horn, H.M., and J.D. Van Ryzin, "Deep Ocean Polyethylene Pipe Installations," *Proceedings, International Pipeline Technology Exhibition Conference (Interpipe 80)*, Vol. 1, Houston, TX, 1980.

38. Nihous, G., and L. Vega, *Bottom-Mounted OTEC Seawater Systems Workshop—Summary Report*, Pacific International Center for High Technology Research, April 1988, Kailua-Kona, Hawaii, Golden, CO: Solar Energy Research Institute, in press.

39. Fast, A.W., and K.Y. Tanoue, eds., *OTEC Aquaculture in Hawaii*, Publication No. UNHI Seagrant 89-01, Honolulu: University of Hawaii Seagrant Program, 1988.

40. U.S. Department of Energy, *Comprehensive Ocean Thermal Technology Applications and Market Development (TAMD) Plan*, Sixth Annual Update to Congress in response to PL 96-310, April 4, 1989, Washington, DC.

41. Solar Energy Research Institute, *Environmental Impact of Ocean Thermal Energy Conversion*, SERI/SP-271-2796, Golden, CO: Solar Energy Research Institute, 1986.

42. Sullivan, J.M., et al., *Environmental Assessment, Ocean Thermal Energy Conversion Pilot Plants*, DOE/EA-0147, Washington, DC: U.S. Department of Energy, 1981.

43. Green, H.J., and P.R. Guenther, "Carbon Dioxide Release from OTEC Cycles," to be presented at the American Society of Civil Engineers International Conference on Ocean Energy Recovery, Honolulu, Hawaii, November 28–30, 1989. New York: ASCE, in press.

44. American Society of Civil Engineers, *Compendium of International Ocean Energy Activities*, New York, 1989.

45. Yamanaka, N., T. Ohnishi, and N. Takatsu, "OTEC in Okinawa," *Proceedings, Fifth International Offshore Mechanics and Arctic Engineering Symposium*, Tokyo, Japan, April 13–18, New York: The American Society of Mechanical Engineers, 1986, pp. 585–592.

46. Liao, T., et al., "Feasibility and Concept Design Studies for OTEC Plants along the East Coast of Taiwan, Republic of China," *Proceedings, Fifth International Offshore Mechanics and Arctic Engineering Symposium*, Tokyo, Japan, April 13–18, New York: American Society of Mechanical Engineers, 1986, pp. 618–625.

47. Johnson, F.A., "Energy from the Oceans: A Small Land-Based Ocean Thermal Energy Plant," *Proceedings, EEZ Resources Technology Assessment*, Honolulu, Hawaii, January 1988.

Appendix

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