OCEAN THERMAL ENERGY CONVERSION

Ocean thermal energy conversion (OTEC) indirectly converts solar energy into electricity. From a thermodynamic perspective, OTEC power cycles operate as continuous heat engines driven by the transfer of energy between a thermal source and sink. OTEC expends renewable solar energy; therefore, recurring costs to generate electrical power are minimal. However, the fixed or capital costs of OTEC systems per kilowatt of installed generating capacity are very high. This is a consequence of the low theoretical efficiency of OTEC, which demands large components, such as heat exchangers and pipelines, to accommodate the thermal energy transfers necessary to produce small amounts of electricity. The high fixed costs dominate the economics of OTEC to the extent that it currently cannot compete with conventional power systems except in limited niche markets. Toward this end, considerable effort has been expended over the past two decades to develop OTEC by-products, such as freshwater, air condition-

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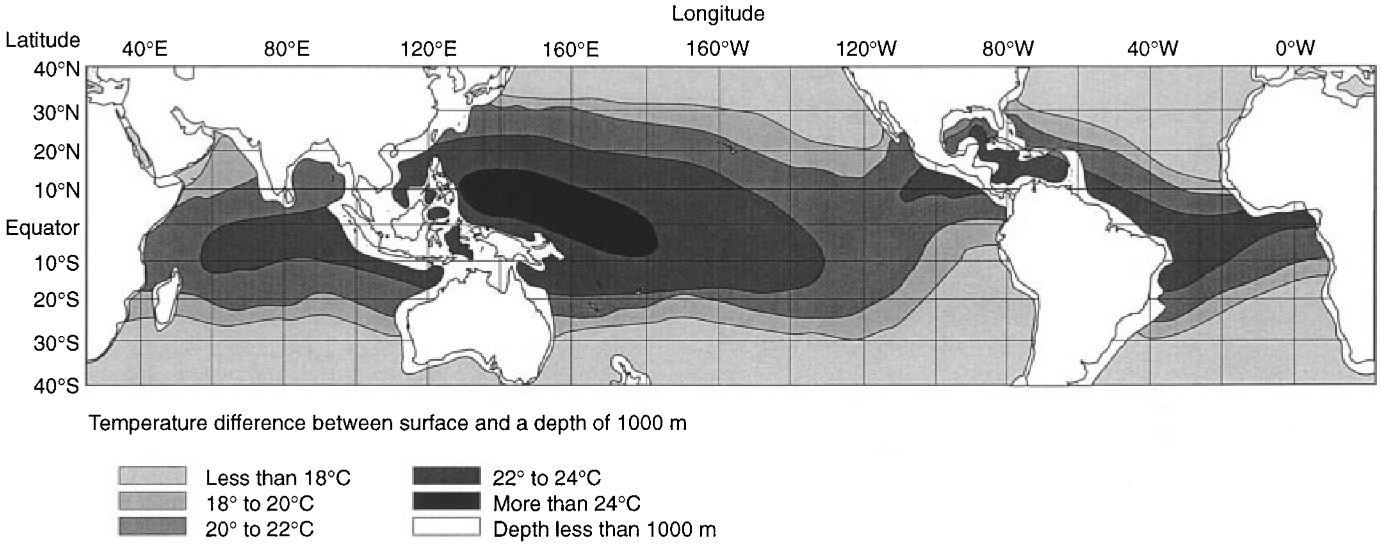

Figure 1. Temperature difference between surface seawater and ocean depths of 1000 m.

ing, and mariculture, that might offset the cost penalty of electricity generation.

Warm surface waters of tropical oceans make up the thermal resource used by OTEC. The oceans, which cover more than 70% of the earth's surface, intercept solar radiation passing through the atmosphere. Even though a portion of this energy is reradiated directly back to space, a significant fraction is retained by seawater at the lower latitudes, heating the upper mixed layer of tropical oceans to an average year-round temperature of approximately 28°C. This energy is subsequently advected to higher latitudes—where radiant losses exceed gains—by oceanic and atmospheric circulation (the net transfer of energy between the earth and its surroundings must, of course, be zero in order to maintain equilibrium). The amount of solar radiation retained by the oceans is enormous. Each day, energy equivalent to approximately 250 billion barrels of oil is absorbed over the 60 million km^2 of tropical seas (1). This is more than three orders of magnitude greater than the current daily energy consumption of the world's population.

Inasmuch as the second law of thermodynamics dictates that only a fraction of the energy extracted from warm seawater can be converted to usable work by a power cycle, a thermal sink must be available to accept waste heat. The oceans provide such a sink in the form of a bottom layer of cold water lying beneath the warm, well-mixed (by wind and waves) surface zone. This reservoir of cold water forms in the polar regions and descends to flow along the sea floor toward the equator (2). The warm surface layer, which can extend to depths of 100 m, is separated from the deep cold water by a thermocline. The vertical gradient in temperature below the mixed layer is usually substantial. The temperature difference between the surface and 1000 m depth ranges from 10 to 25°C, with larger differences occurring in equatorial and tropical waters.

The performance of OTEC power cycles depends ultimately on the available difference in the temperatures of the warm and cold seawater ΔT. The rule of thumb is that a ΔT of about 20°C is necessary to sustain viable operation of an OTEC power station. As shown in Fig. 1, which maps average ΔT between the surface and 1000 m, this requirement limits the number of candidate OTEC sites. One of the principal technical challenges of recent years, therefore, has been to devise strategies to export the benefits of the renewable OTEC resource to locations outside the tropics, possibly through the production of synthetic fuels, such as the generation of hydrogen gas by electrolysis.

HISTORY OF OTEC

The OTEC concept was first proposed in 1881 by the French engineer J. A. D'Arsonval. D'Arsonval recommended using pressurized, liquefied gases as working fluids in a heat engine operating across the temperature difference between the surface and deep waters of the equatorial oceans. A half-century later, in 1930, G. Claude, D'Arsonval's former student, field-tested a variation of the OTEC concept in northern Cuba. Claude's power cycle used warm seawater evaporated in a partial vacuum as a working fluid. His shore-based, 50 kW plant consumed more power than it generated because of an overly conservative cold seawater system that pumped 10 times more water than required. The plant operated for 11 days before the cold water pipe failed in a storm. In spite of its shortcomings, the experiment was the first to demonstrate clearly the technical feasibility of OTEC. Encouraged by the Cuba tests, Claude launched a second attempt in 1933 to develop OTEC, this time in the form of a plantship moored about 100 km off the Brazilian coast. The power system was sized to produce 2 MW of turbine shaft power. Rather than attempt to export this power to the coastline directly, Claude decided to produce ice, which had a favorable market value. Unfortunately, the expensive vertical cold water pipeline was lost during deployment, resulting in cancellation of the project. Although Claude continued to champion OTEC, the goal of an operating commercial plant was to elude him.

Following the 1933 project, several OTEC design studies were conducted. In 1956, a French team was preparing to install a shore-based, 5 MW Claude cycle plant at a site on the west coast of Africa. The project was abandoned when it was announced that a large hydroelectric station would be constructed nearby. During the 1960s, J. H. Anderson and his son published plans for a 100 MW floating OTEC power plant that revived D'Arsonval's original concept of using a pressurized, low boiling point gas (propane) as a working fluid in a Rankine power cycle. Although the public and private sectors remained indifferent, the Andersons' advocacy of OTEC attracted several key supporters in the early 1970s, notably W. E. Heronemus of the University of Massachusetts and C. Zener of Carnegie-Mellon University. In 1972, the National Science Foundation awarded a grant to the University of Massachusetts to assess the technical and economic feasibility of the OTEC process. A second grant was awarded a year later to Carnegie-Mellon to investigate other elements of the OTEC system.

The oil embargo of 1973 to 1974, combined with growing public concerns over the safety of nuclear power, forced the world to reassess its dependence on fossil fuels and triggered a frantic search for alternative energy resources. Interest in OTEC therefore enjoyed a sudden resurgence, and numerous development projects were initiated throughout the world.

Several milestones in OTEC research and development have been achieved since that time. In 1979, a consortium of private businesses led by Lockheed Missiles & Space Company and the Dillingham Corporation, in partnership with the Hawaii state government, began operation of the first floating OTEC plant to produce net power. Named Mini-OTEC, the plant was anchored off the western coast of the island of Hawaii. The ammonia Rankine cycle produced about 50 kW at the generator terminals and provided over 600 hours of data over three months. Two years later, Japanese researchers began operation of a shore-based 100 kW Rankine cycle plant on the island of Nauru in the south Pacific. Tests were conducted for about one year. A record power output of 120 kW (gross) was attained before the cold water pipeline was damaged by a storm. A nominal 210 kW Claude cycle OTEC plant has been producing electricity since 1993 at the Natural Energy Laboratory of Hawaii, also on the island of Hawaii. The facility, which is operated by the Pacific International Center for High Technology Research (PICHTR), is funded by the U.S. Department of Energy and Hawaii state government. Over the past three years, it has set new records for both gross (255 kW) and net (103 kW) electrical power. It also has successfully produced potable water.

Although funding for recent OTEC programs has waxed and waned over the more than 20 years since the first oil embargo, research and development activities have significantly advanced OTEC technology. Unfortunately, none of the programs to date has taken the critical step of constructing and operating the first commercial-scale (MW scale) pilot OTEC power station. Until this happens, the vast OTEC energy resource will continue to remain untapped.

PRINCIPLES OF OPERATION

OTEC power systems operate as cyclic heat engines. They receive thermal energy through heat transfer from a resource, here, surface seawater warmed by the sun, and transform a portion of this energy into electrical power. The Kelvin-Planck statement of the second law of thermodynamics precludes complete conversion of the thermal energy into electricity. A portion of the heat extracted from the warm seawater must be rejected to a colder thermal sink. The thermal sink employed by OTEC systems is seawater drawn from the ocean depths by means of a submerged pipeline.

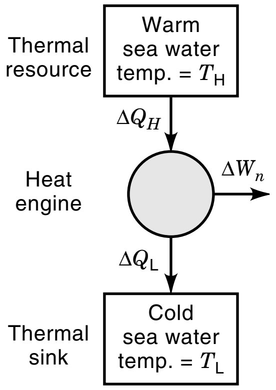

Figure 2. Cyclic OTEC heat engine.

The essential features of a cyclic OTEC heat engine are presented in Fig. 2. A steady state control volume energy analysis yields the result that net electrical power produced by the engine must equal the difference of the rates of heat transfer from the warm surface water to the cold deep water or, using the notation in Fig. 2,

$$\Delta W_n = \Delta Q_H - \Delta Q_L \tag{1}$$

The conversion efficiency η of a heat engine is the ratio of usable power generated to thermal energy received:

$$\eta = \Delta W_n / \Delta Q_H \tag{2}$$

This efficiency is maximized when entropy production is zero (i.e., when the engine operates reversibly). Such an ideal device is called a Carnot heat engine, and its performance establishes an upper bound for real thermal power generation systems. The theoretical Carnot efficiency is a function only of the absolute temperatures of the thermal resource T_H and thermal sink T_L:

$$\eta = 1 - (T_L/T_H) = \Delta T/T_H \tag{3}$$

Assuming a maximum ocean surface temperature T_H of about 30°C (303 K) and a typical deep seawater temperature T_L of 4°C (277 K), the limiting performance of OTEC power systems is

$$\eta = 1 - (277/303) = 0.086 \text{ or } 8.6\% \tag{4}$$

This implies that more than 90% of the thermal energy extracted from the ocean's surface is "wasted" and must be rejected to the cold, deep seawater. The low efficiency of OTEC necessitates large heat exchangers and seawater flow rates to sustain the ΔQ's needed to produce relatively small amounts of electricity. In contrast, the Carnot efficiency of a state-of-the-art combustion steam power cycle, which taps a much higher temperature energy source, may exceed 60%. The lower thermal quality of the OTEC resource, therefore, imposes a significant penalty on the heat engine that ultimately is manifested in high capital costs.

In spite of its inherent inefficiency, OTEC, unlike conventional fossil energy systems, uses a renewable resource and poses a minimal threat to the environment.

Carnot efficiency applies only to an ideal heat engine. In actual OTEC systems, irreversibilities will further degrade cycle performance from the already low theoretical limit. Successful implementation of OTEC power generation thereby demands careful engineering to minimize irreversibilities. Although OTEC consumes what is essentially a free resource, poor thermodynamic performance will reduce the quantity of electricity available for sale and, hence, will negatively affect the economic feasibility of an OTEC facility by increasing the payback period for capital investments.

The OTEC heat engine may be configured following designs proposed by D'Arsonval or Claude, known, respectively, as closed cycle and open cycle OTEC. The following sections provide additional technical information on these two power cycles and their variants, as well as a hybrid cycle that produces electricity and potable water.

CLOSED CYCLE OTEC

D'Arsonval's original concept for OTEC proposed to use a pure working fluid that would evaporate at the temperature of warm seawater. The vapor would subsequently expand and do work before being condensed by the cold seawater. This series of steps would be repeated continuously using the same working fluid, whose flow path and thermodynamic process representation constituted closed loops—hence, the name *closed cycle.* The specific process adopted for closed cycle OTEC is the Rankine, or vapor power, cycle.

Figure 3 is a simplified schematic diagram of a closed cycle OTEC system. The principal components are the heat exchangers, turbogenerator, and seawater supply system, which, although not shown, accounts for most of the parasitic power consumption and a significant fraction of the capital expense. Also not included in the schematic are ancillary devices such as separators to remove residual liquid downstream of the evaporator and subsystems to hold and supply make-up working fluid lost through leaks or contamination.

In a closed cycle system, heat transfer from warm surface seawater occurs in the evaporator, producing a saturated vapor from the liquid working fluid. Electricity is generated when this gas expands to lower pressure through the turbine. Latent heat is transferred from the vapor to the cold seawater in the condenser, and the resulting liquid is pressurized with a pump to begin the cycle again.

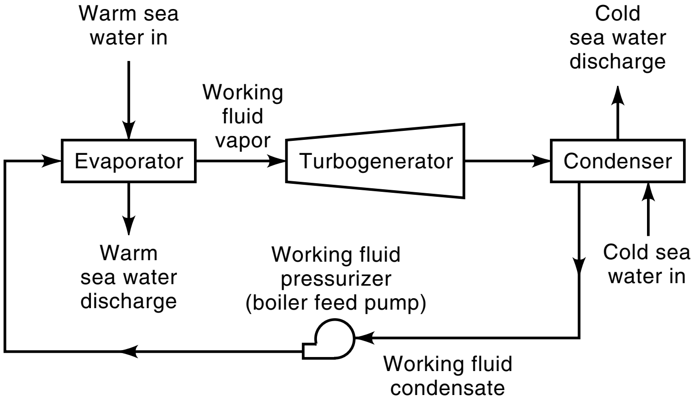

Figure 3. Schematic diagram of a closed cycle OTEC system.

The success of the Rankine cycle is a consequence of more energy being recovered when the vapor expands through the turbine than is consumed in repressurizing the liquid. In conventional (e.g., combustion) Rankine systems, this yields net electrical power. For OTEC, however, the remaining balance may be reduced substantially by an amount needed to pump large volumes of seawater through the heat exchangers. Representative values of closed cycle OTEC back-work are provided in an example that follows.

One misconception about OTEC is that tremendous energy must be expended to bring cold seawater up from depths approaching 1000 m against the force of gravity. In reality, the natural hydrostatic pressure gradient provides for most of the increase in the gravitational potential energy of a fluid particle moving with the gradient from the ocean depths to the surface. This can be seen by writing the modified Bernoulli equation for a submerged pipeline, with intake at depth z_1 discharging at sea level z_2. The work ΔW required to move a unit mass of seawater through this simple pipe is

$$\Delta W \approx [(P_2 - P_1)/\rho] + [(V_2^2 - V_1^2)/2] + [g(z_2 - z_1)] + \Sigma[(fLV^2)/(2D)] \tag{5}$$

where V is the local mean velocity; g is the gravitational acceleration; f, L, and D are, respectively, the pipe friction factor, length, and inside diameter; and ρ is the seawater density, assumed to be constant (in reality, small variations of ρ with depth occur due to salinity and temperature gradients). The difference in the pressures at the pipe inlet and exit, $P_2 - P_1$, is equivalent to the hydrostatic head:

$$(P_2 - P_1) = \rho g(z_1 - z_2) \tag{6}$$

Hence, the pressure and gravity terms cancel on the right-hand side of the Bernoulli equation. For a constant diameter pipeline, $V_2 = V_1$ and work must be supplied only to overcome frictional losses. In a real OTEC cold water pipeline, some additional work is needed to compensate for the nonuniform seawater density.

Irreversibilities in the turbomachinery and heat exchangers reduce cycle efficiency below the Carnot value. Irreversibilities in the heat exchangers occur when energy is transferred over a large temperature difference. It is important, therefore, to select a working fluid that will undergo the desired phase changes at temperatures established by the surface and deep seawater. Insofar as a large number of substances can meet this requirement (because pressures and the pressure ratio across the turbine and pump are design parameters), other factors must be considered in the selection of a working fluid including cost and availability, compatibility with system materials, toxicity, and environmental hazard.

Leading candidate working fluids for closed cycle OTEC applications are ammonia and various fluorocarbon refrigerants [i.e., chlorofluorocarbons (CFCs), hydrochlorofluorocarbons (HCFCs), hydrofluorocarbons (HFCs)]. Some of these substances are also used in geothermal power stations and Rankine bottoming cycles. Their primary disadvantage is the environmental hazard posed by leakage, because maximum pressures in OTEC systems using these fluids would lie between 6 and 9 atmospheres (absolute). Ammonia is toxic in moderate concentrations. CFCs have been banned by the Montreal Protocol because they deplete stratospheric ozone. HCFCs and HFCs are major greenhouse gases.

KALINA CYCLE

The Kalina, or adjustable proportion fluid mixture (APFM), cycle is a variant of the OTEC closed cycle. Whereas simple closed cycle OTEC systems use a pure working fluid, the Kalina cycle proposes to employ a binary mixture of ammonia and water with varying proportions at different points in the system. The advantage of a binary mixture is that, at a given pressure, evaporation or condensation occurs over a range of temperatures; a pure fluid, on the other hand, changes phase at constant temperature. This additional degree of freedom allows heat transfer-related irreversibilities in the evaporator and condenser to be reduced (3). The local temperature gap between the working fluid and the seawater flowing through the heat exchanger can, within limits, be manipulated, with a resulting improvement in cycle thermodynamic efficiency.

A schematic diagram of an OTEC Kalina cycle is provided in Fig. 4. As expected, even though it is similar to a simple closed cycle OTEC system, several additional components are added to accommodate the binary fluid and to provide means to adjust the proportions of the ammonia and water flowing through the different devices. Saturated two-phase flow entering the separator is divided into an ammonia-rich vapor stream and water-rich liquid. The vapor expands through the turbine before mixing with and being absorbed into the depressurized liquid. Phase change begins and ends at higher temperatures as the mass fraction of ammonia in the mixture decreases.

Uehara and Ikegami analyzed the performance of an optimized Kalina cycle and a simple ammonia closed cycle OTEC system (4). For warm and cold seawater temperatures of 28 and 4°C, respectively, they concluded that the Kalina cycle would improve cycle efficiency (neglecting back-work expended to pump seawater) by about one percentage point, from approximately 4% to 5%.

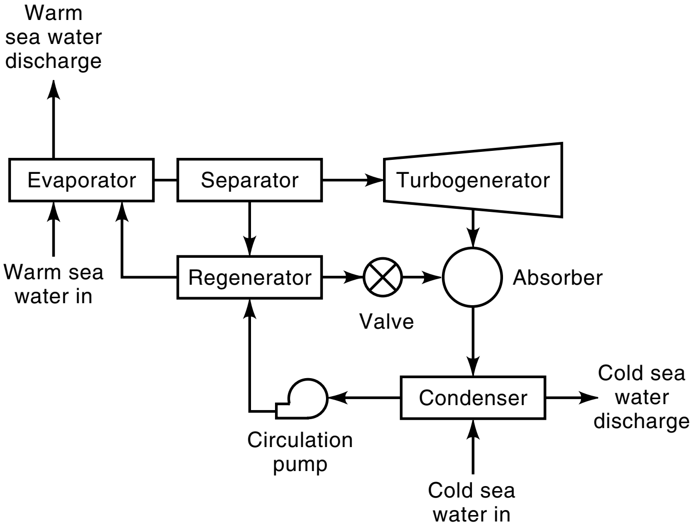

Figure 4. Schematic diagram of a Kalina cycle OTEC system.

Even though a 25% performance improvement is significant, the Kalina cycle needs additional capital equipment, and may impose severe demands on the evaporator and condenser. The efficiency improvement arises largely as a result of reducing the temperature difference over which heat transfer occurs in these devices; therefore, maintaining a given ΔQ will require some combination of higher heat transfer coefficients, more heat transfer surface area, and increased seawater flow rates. Each of these changes has an associated cost or power penalty. Additional analysis and testing must be conducted to determine whether the Kalina cycle is appropriate for OTEC applications.

OPEN CYCLE OTEC

Claude's concern about the cost and potential biofouling of closed cycle heat exchangers led him to propose using steam generated directly from the warm seawater as the OTEC working fluid. The steps of the Claude, or open, cycle are (1) flash evaporation of warm seawater in a partial vacuum, (2) expansion of the steam through a turbine to generate power, (3) condensation of the vapor by direct contact heat transfer to cold seawater, and (4) compression and discharge of the condensate and any residual noncondensable gases. Unless freshwater is a desired by-product, open cycle OTEC eliminates the need for surface heat exchangers. The name *open cycle* comes from the fact that the working fluid (steam) is discharged after a single pass and has different initial and final thermodynamic states; hence, the flow path and process are open.

The essential features of an open cycle OTEC system are presented in Fig. 5. The entire system, from evaporator to condenser, operates at partial vacuum, typically at pressures between 1% and 3% of atmospheric. Initial evacuation of the system and removal of noncondensable gases during operation are performed by the vacuum compressor, which, along with the seawater and discharge pumps, accounts for the bulk of the open cycle OTEC parasitic power consumption (i.e., back-work).

The low system pressures of open cycle OTEC are necessary to induce boiling of the warm seawater. Flash evaporation is accomplished by exposing the seawater to pressures below the saturation pressure corresponding to its temperature, which, at 28°C is about 3780 Pa. This is usually accomplished by pumping it into an evacuated chamber through spouts designed to maximize heat and mass transfer surface area. Removal of gases dissolved in the seawater, which will come out of solution in the low-pressure evaporator and compromise operation, may be performed at an intermediate pressure prior to evaporation.

Vapor produced in the flash evaporator is relatively pure steam. The heat of vaporization is extracted from the liquid phase, lowering its temperature and preventing any further boiling. Flash evaporation may be perceived, then, as a transfer of thermal energy from the bulk of the warm seawater to the small fraction of mass that is vaporized. Less than 0.5% of the mass of warm seawater entering the evaporator is converted into steam.

The pressure drop across the turbine is established by the cold seawater temperature. At 4°C, steam condenses at 813 Pa. The turbine (or turbine diffuser) exit pressure cannot fall

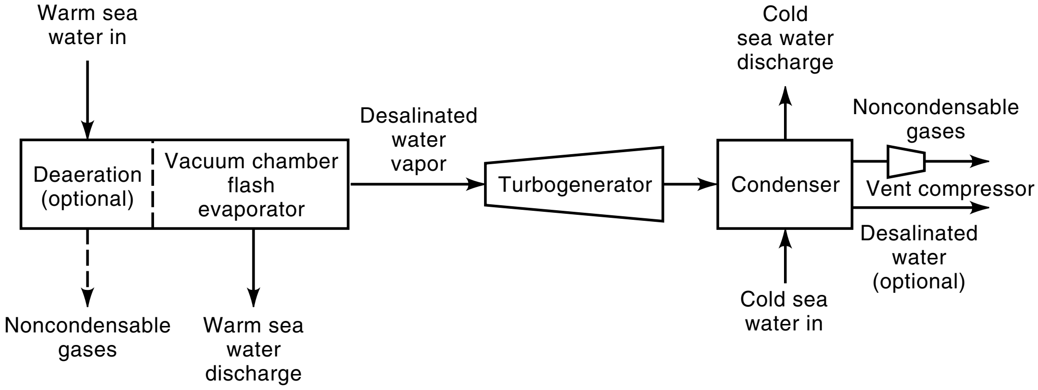

Figure 5. Schematic diagram of an open cycle OTEC system.

below this value. Hence, the maximum turbine pressure drop is only about 3000 Pa, corresponding to about a 3 : 1 pressure ratio. This will be further reduced to account for other pressure drops along the steam path and differences in the temperatures of the steam and seawater streams needed to facilitate heat transfer in the evaporator and condenser. For example, the nominal 210 kW PICHTR open cycle OTEC plant in Hawaii operates with a turbine pressure drop of about 1200 Pa when the warm and cold seawater temperatures are 27.5°C and 6°C, respectively (5). The maximum theoretical pressure drop for these conditions is approximately 2700 Pa.

Condensation of the low-pressure steam leaving the turbine may employ a direct contact condenser (DCC) in which cold seawater is sprayed over the vapor, or a conventional surface condenser that physically separates the coolant and the condensate. DCCs are inexpensive and have good heat transfer characteristics because they lack a solid thermal boundary between the warm and cool fluids. Surface condensers are expensive and more difficult to maintain than DCCs; however, they produce a marketable freshwater by-product.

Effluent from the condenser must be discharged to the environment. Liquids are pressurized to ambient levels at the point of release by means of a pump, or, if the elevation of the condenser is suitably high, they can be compressed hydrostatically. As noted previously, noncondensable gases, which include any residual water vapor, dissolved gases that have come out of solution, and air that may have leaked into the system are removed by the vacuum compressor.

Open cycle OTEC eliminates expensive heat exchangers at the cost of low system pressures. Partial vacuum operation has the disadvantage of making the system vulnerable to air in-leakage and promotes the evolution of noncondensable gases dissolved in seawater. Power must ultimately be expended to pressurize and remove these gases. Furthermore, as a consequence of the low steam density, volumetric flow rates are very high per unit of electricity generated. Large components are needed to accommodate these flow rates. In particular, only the largest conventional steam turbine stages have the potential for integration into open cycle OTEC systems of a few megawatts gross generating capacity. It is generally acknowledged that higher capacity plants will require a major turbine development effort (6).

MIST AND FOAM LIFT OTEC CYCLES

The mist lift and foam lift OTEC systems are variants of the OTEC open cycle. Both employ the seawater directly to produce power. Unlike Claude's open cycle, lift cycles generate electricity with a hydraulic turbine. The energy expended by the liquid to drive the turbine is recovered from the warm seawater (7).

Figure 6 outlines the concept of OTEC lift cycles. In the lift process, warm seawater is flash evaporated to produce a

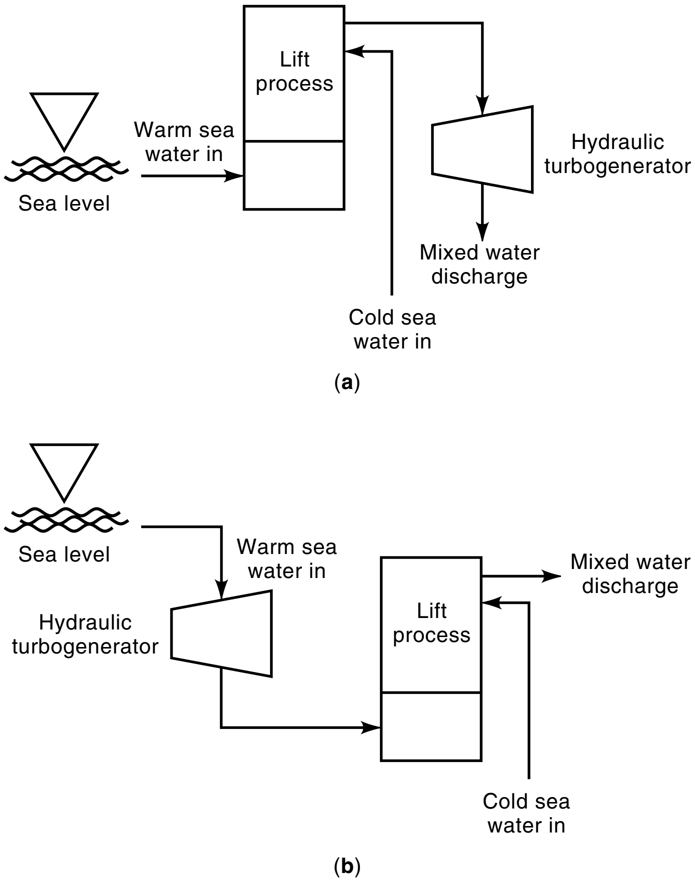

Figure 6. Schematic diagram of (a) mist lift and (b) foam lift OTEC systems.

two-phase, liquid-vapor mixture—either a mist consisting of liquid droplets suspended in a vapor, or a foam, where vapor bubbles are contained in a continuous liquid phase. The mixture rises, doing work against gravity. Here, the thermal energy of the vapor is expended to increase the potential energy of the fluid. The vapor is then condensed with cold seawater and discharged back into the ocean. Flow of the liquid through the hydraulic turbine may occur before or after the lift process.

Advocates of the mist and foam lift cycles contend that they are cheaper to implement than closed cycle OTEC because they require no expensive heat exchangers and are superior to the Claude cycle because they use a hydraulic turbine rather than a low pressure steam turbine. These claims await verification.

HYBRID CYCLE OTEC

The power generation capacity of the Claude open cycle is limited to a few megawatts by existing low pressure steam turbine technology. This is not the case for closed cycle OTEC, which, because it uses a pressurized working fluid, does not need to sustain comparable volumetric flow rates of vapor. Closed cycle design studies have identified commercial turbomachinery that can be used to generate up to 100 MW of electrical power. On the other hand, open cycle OTEC has the benefit of being able to produce potable water. Some marketing studies have suggested that OTEC systems that can provide both electricity and water may be able to penetrate the marketplace more readily than plants dedicated solely to power generation. Hybrid cycle OTEC was conceived as a response to these studies. Hybrid cycles combine the potable water production capabilities of open cycle OTEC with the potential for large electricity generation capacities offered by the closed cycle.

Figure 7 depicts the elements of one type of hybrid OTEC cycle proposed by Panchal and Bell (8). As in the Claude cycle, warm surface seawater is flash evaporated in a partial vacuum. This low-pressure steam flows into a heat exchanger where it is employed to vaporize pressurized ammonia. During this process, most of the steam condenses, yielding desalinated potable water. The ammonia vapor flows through a simple closed cycle power loop and is condensed using cold seawater. The uncondensed steam and other gases exiting the ammonia evaporator may be further cooled by heat transfer to either the liquid ammonia leaving the ammonia condenser or cold seawater. The noncondensables are then compressed and discharged to the atmosphere.

Steam is used as an intermediary heat transfer medium between the warm seawater and the ammonia; consequently, the potential for biofouling in the ammonia evaporator is reduced significantly. Another advantage of the hybrid cycle related to freshwater production is that condensation occurs at significantly higher pressures than in an open cycle OTEC condenser, as a result of the elimination of the turbine from the steam flow path. This may, in turn, yield some savings in the amount of power consumed to compress and discharge the noncondensable gases from the system. These savings (relative to a simple Claude cycle producing electricity and water), however, are offset by the additional back-work of the closed cycle ammonia pump.

One drawback of the hybrid cycle shown in Fig. 7 is that water production and power generation are closely coupled. Changes or problems in either the water or power subsystem will compromise performance of the other. Furthermore, there is a risk that the potable water may be contaminated by an ammonia leak. In response to these concerns, an alternative hybrid cycle, comprising decoupled power and water production components, has been proposed (9). The basis for this concept lies in the fact that warm seawater leaving a closed cycle evaporator is still sufficiently warm, and cold seawater exiting the condenser is sufficiently cold, to sustain an independent freshwater production process.

The alternative hybrid cycle consists of a conventional closed cycle OTEC system that produces electricity and a downstream flash-evaporation-based desalination system. Seawater from the closed cycle evaporator, which typically has been cooled by about 3°C, is pumped into a flash evaporator evacuated to below the water's corresponding saturation pressure. The desalinated steam produced is condensed in a surface heat exchanger by heat transfer to the effluent cold seawater from the closed cycle condenser. Depending on the configuration of the closed cycle power system, the cold seawater may experience up to a 6°C temperature rise as it passes through the closed cycle condenser. Although the initial power generation step can reduce the ΔT of the warm and cold seawater by about 9° to 10°C—from, say, 24° to 14°C—this is still adequate to accomplish desalination.

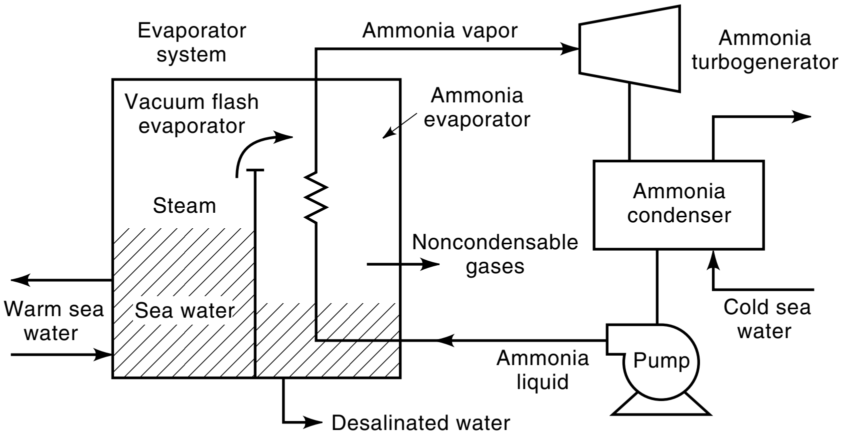

Figure 7. Schematic diagram of hybrid cycle OTEC system.

With the alternative hybrid cycle, water production and electricity generation can be adjusted independently, within limits, in response to demand. Should either subsystem fail or require servicing, the other can continue to operate. The primary drawbacks of the alternative hybrid cycle are that (1) the ammonia evaporator uses warm seawater directly and is therefore subject to biofouling, and (2) additional equipment, such as the potable water surface condenser, is required, increasing capital expenses.

COMPARISON OF OTEC OPEN AND CLOSED CYCLES

It is worthwhile to examine the common elements and points of contrast of the open (Claude) and closed (Rankine) OTEC cycles. Even though the means by which these two primary OTEC strategies exploit the low-quality thermal resource to produce power are quite different, the end results are similar. The small temperature difference between surface and deep seawater establishes an upper limit on the thermodynamic conversion efficiency of any heat engine to about 8%. Irreversibilities in devices such as heat exchangers and turbomachinery, and back-work associated with pumping the large volumes of seawater required to sustain operation, make it unlikely that OTEC plant efficiency (as a percentage of thermal energy extracted from the warm seawater that ultimately is available for export and sale as electricity) will exceed 2% to 3%. Analyses have determined that, for comparable power-generating capacity, the thermal performance of the two cycles does not differ significantly. Even though the direct contact heat exchangers employed in an open cycle system have the potential to use more fully the thermal seawater resource, irreversibilities associated with the vacuum compressor system and noncondensable gases reduce this advantage in practice.

Both open and closed cycles require similar volumes of seawater to produce a unit of electrical power. For megawatt-scale plants operating over a seawater temperature difference of 20°C, about 3.5 m^3/s of warm surface water must be supplied per megawatt of electricity generated by the turbine. Studies suggest that net power output is optimized when warm-to-cold water ratios lie between 1.8 : 1 and 2 : 1. Back-work to run the seawater pumps and other parasitics accounts for about 30% of the turbine output for larger plants and a higher percentage of the gross in smaller facilities. This suggests that 5 m^3/s of warm seawater are needed for each megawatt of electricity available for sale. An OTEC plant producing 20 MW at the generator terminals will therefore be able to export 14 MW to the grid and will require 70 m^3/s (70000 L/s) of warm seawater and about 35 m^3/s (35000 L/s) of cold seawater. Seawater velocities have to be maintained below 2 m/s to control pumping power losses; as such, the submerged intake pipeline diameter scales as 1.8 m/MW (net) on the warm water side and 1.2 m/MW (net) on the cold water side. It is obvious that the huge pipelines or pipe arrays needed to supply seawater to a commercial OTEC plant represent a serious technological challenge and major capital expense.

Open and closed cycles differ primarily in their economics and target markets. Although a Claude cycle dedicated to electricity generation offers potential savings over a closed cycle plant by eliminating the need for expensive evaporators and surface condensers, these savings may be offset partially by the relatively high cost of the low-pressure steam turbine and larger ducting and structures needed to accommodate partial vacuum operation. Because the largest (L-0) existing conventional steam turbine stages will only produce about 2 MW under open cycle OTEC conditions, multimegawatt open cycle installations probably will need to be configured, in the near-term, using multiple 2 MW to 4 MW (single or double wheel turbine) power modules. Open cycle OTEC is therefore believed to be best suited to rural sites with low power demand and a need for the potable water by-product. Heat exchangers notwithstanding, pressurized closed cycle systems, which are relatively compact, can easily generate tens of megawatts of electricity using existing technology. The current consensus is that closed cycle OTEC may be successfully integrated into urban energy strategies or employed to power OTEC plantship operations.

OPEN AND CLOSED CYCLE OTEC SYSTEM PERFORMANCE

Tables 1 and 2 present the results of design studies of open and closed cycle OTEC plants. Table 1 corresponds to a shore-based open cycle plant producing both electricity and freshwater (10). The system has been optimized for power generation. For a seawater ΔT of 22°C, the plant can provide about 1.2 MW of electricity to the local power grid and supply 2200 m^3 (2.2×10^6 L) of freshwater per day. Table 2 describes the simulated operation of a larger, ammonia closed cycle OTEC power system designed for installation on a floating platform

Table 1. Open Cycle OTEC System Performance Summary

Warm water pipe inner diameter	2.5 m
Cold water pipe outer diameter	1.6 m
Mixed discharge pipe outer diameter	3 m
Cold water pipe intake depth	1000 m
Gross power	1838 kW
Parasitic power (back-work)	595 kW
Back-work ratio	32%
Net power	1243 kW
Fresh (potable) water production	25.9 kg/s (1550 l/min)
Warm seawater flow rate	5978 kg/s (5.85 m^3/s)
Cold seawater flow rate	3085 kg/s (3.0 m^3/s)
Warm seawater supply temperature	26 °C
Cold seawater supply temperature	4 °C
Steam flow rate through turbine	26.1 kg/s
Turbine inlet temperature	22.7 °C
Turbine inlet pressure	2.74 kPa
Turbine outlet temperature	11.1 °C
Turbine outlet pressure	1.29 kPa
Turbine rotor diameter	5.65 m
Warm seawater pump power	183 kW
Cold seawater pump power	324 kW
Vent (vacuum) compressor power	80 kW
Potable water storage pump power	8 kW
Carnot efficiency	0.0735 (7.35%)
Thermal energy from warm seawater	63531 kJ/s
Cycle efficiency based on gross turbine power	0.029 (2.9%)
Cycle efficiency based on net power	0.020 (2.0%)

Table 2. Closed Cycle OTEC System Performance Summary

Warm water pipe inner diameter	4.6 m
Cold water pipe outer diameter	2.74 m
Mixed discharge pipe outer diameter	5.5 m
Cold water pipe intake depth	1000 m
Gross power	7920 kW
Parasitic power (back-work)	2660 kW
Back-work ratio	34%
Net power	5260 kW
Warm seawater flow rate	27000 kg/s (26.4 m^3/s)
Cold seawater flow rate	14240 kg/s (13.9 m^3/s)
Warm seawater supply temperature	26 °C
Cold seawater supply temperature	4.5 °C
Warm water return temperature	22.9 °C
Cold water return temperature	10.3 °C
Ammonia flow rate through turbine	274 kg/s
Turbine inlet temperature	21.1 °C
Turbine inlet pressure	890 kPa
Turbine outlet temperature	11.9 °C
Turbine outlet pressure	656 kPa
Warm seawater pump power	640 kW
Cold seawater pump power	1150 kW
Mixed discharge seawater pump power	680 kW
Ammonia pump power	190 kW
Carnot efficiency	0.0719 (7.19%)
Thermal energy from warm seawater	336176 kJ/s
Cycle efficiency based on gross turbine power	0.024 (2.4%)
Cycle efficiency based on net power	0.016 (1.6%)

(9). A net power output of 5.3 MW is calculated for a slightly smaller seawater ΔT of 21.5°C.

In both systems, back-work, primarily to operate the seawater pumps, consumes slightly in excess of 30% of the power generated by the turbine. Even though the Carnot efficiencies are about 7%, irreversibilities and system parasitics greatly degrade performance. Less than 2% of the thermal energy extracted from the warm seawater is exported as electricity by the open cycle plant. The closed cycle plant only attains about 80% of this low value—its net power efficiency is slightly more than 1.6%. The marginally better open cycle performance can be attributed to the superior heat transfer characteristics of the direct contact flash evaporator relative to the ammonia evaporator.

ENVIRONMENTAL CONSIDERATIONS

OTEC systems are, for the most part, environmentally benign. Even though accidental leakage of closed cycle working fluids can pose a hazard, under normal conditions, the only effluents are the mixed seawater discharges and dissolved gases that come out of solution when seawater is depressurized.

OTEC mixed seawater discharges will be at lower temperatures than seawater at the ocean surface. The discharges also will contain high concentrations of nutrients brought up with the deep seawater and may have a different salinity. It is important, therefore, that release back into the ocean be conducted in a manner that minimizes disruptions to the ocean mixed layer biota and avoids inducing long-term surface temperature anomalies. Analyses of OTEC effluent plumes suggest that discharge between the 50 m and 100 m depths should be sufficient to ensure minimal impact on the ocean environment.

The extent of outgassing from seawater typically will be greater in open cycle plants than in closed cycle systems because water-side pressures are low in the flash evaporator and in the condenser, if a DCC is employed. Outgassing also will occur when cold seawater is brought up from the depths to the ocean surface. Although the mass of gas released per unit of seawater is quite small, the massive volumes of water used in OTEC may result in nonnegligible emissions. Fortunately, these gas emissions generally comprise benign species (e.g., N_2, O_2, CO_2); however, CO_2 emissions from OTEC have been investigated in consideration of its role as a greenhouse gas. It is believed that open cycle plants will release between 6 g and 38 g of CO_2/kWh, whereas closed cycle systems have an upper bound of 17 g/kWh. These values compare very favorably with fossil fuel combustion power stations, which emit one to two orders of magnitude more CO_2.

ECONOMICS OF OTEC

Studies conducted to date on the economic feasibility of OTEC systems suffer from the lack of reliable cost data. Commercialization of the technology is unlikely until a full-scale plant is constructed and operated continuously over an extended period to provide these data on capital and recurring expenses (10). Only this type of demonstration will be sufficient to allay the doubts of potential investors and funding agencies.

Uncertainties in financial analyses notwithstanding, projections suggest very high first costs for OTEC power system components (11). Small land-based or near-shore floating plants in the 1 MW to 10 MW (net) range, which would probably be constructed in rural island communities, may require expenditures of between $10,000 and $20,000 (in 1995 US dollars) per kilowatt of installed generating capacity. Even though there appears to be favorable economies of scale, larger floating (closed cycle) plants in the 50 MW to 100 MW range are still anticipated to cost about $5000/kW. This is well in excess of the $1000 to $2000/kW capital expense of fossil fuel combustion power stations. Although the OTEC energy resource is free, low recurring costs will only partially offset the capital cost disadvantage of OTEC power systems.

To enhance the economics of OTEC power stations, various initiatives have been proposed based on marketable OTEC by- or co-products, such as potable water, air conditioning, refrigeration, mariculture, and high-value energy carriers (11,12). OTEC proponents believe that the first commercial OTEC plants will be shore-based systems designed for use in developing Pacific island nations, where potable water is in short supply. Many of these sites would be receptive to opportunities for economic growth provided by OTEC-related industries. Even though some of the by- and co-product concepts have been tested successfully on a small scale, development of commercial-size operations has been hampered by the absence of an full-scale operational OTEC plant. Several of the product options are described below.

Freshwater

The condensate of the open and hybrid cycle OTEC systems is desalinated water, suitable for human consumption and agricultural uses. Analyses have suggested that first-generation OTEC plants, in the 1 MW to 10 MW range, would serve the utility power needs of rural Pacific island communities, with the desalinated water by-product helping to offset the high cost of electricity produced by the system (11).

Refrigeration and Air Conditioning

The cold deep seawater can be used to maintain cold storage spaces and to provide air conditioning. The Natural Energy Laboratory of Hawaii (NELH), the site of Hawaii's OTEC experiments, has air conditioned its buildings by passing the cold seawater through heat exchangers. Similar small-scale operations would be viable in other locales. Economic studies have been performed for larger metropolitan and resort applications. Air conditioning of new developments, such as resort complexes, with cold seawater may be economically attractive even if inexpensive utility-grid electricity is available (13).

Mariculture

The cold deep ocean waters are rich in nutrients and low in pathogens and, therefore, provide an excellent medium for the cultivation of marine organisms. The 322-acre NELH has been the base for successful mariculture research and development enterprises. The site has an array of cold water pipes, originally installed for the early OTEC research but since used for mariculture. The cold water is used to cultivate salmon, trout, *opihi* (limpet; a shellfish delicacy), oysters, lobsters, sea urchins, abalone, kelp, *nori* (a popular edible seaweed used in sushi), and macro- and microalgae. The earliest experiments on the productivity of this water centered on nori. Phenomenal daily biomass growth rates of 40% to 45% were recorded, and this research has since developed into a commercial enterprise. Even though the techniques used for mariculture remain largely proprietary to the individual entrepreneurs, the commercial success of these fledgling enterprises has been one important indicator of the potential for OTEC-related mariculture.

The cold seawater may have applications for open ocean mariculture as well. Natural upwelling of deep ocean water occurs off the west coasts of North America, South America, West Africa, and other coastal regions where along-shore winds push surface seawater away from land, allowing the deeper waters to upwell. Stimulated by the elevated nutrient content of this deep water, high fish production has been observed in these areas. These natural upwellings account for 0.1% of the world's oceans surface but yield roughly 44% of the world's fish catch (14). Artificial upwelling, generated for OTEC or exclusively for mariculture, has been suggested as a method of creating new fisheries and marine biomass plantations. Should development proceed as anticipated, open ocean cages can be eliminated, and natural feeding would replace expensive feed with temperature and nutrient differentials being used to keep the fish stock in the kept environment.

Agriculture

An idea initially proposed by S. Siegal of the University of Hawaii involves the use of cold seawater for agriculture. This concept involves burying an array of cold water pipes in the ground to create cool weather growing conditions not found in tropical environments. In addition to cooling the soil, the system also drip irrigates the crop via condensation of moisture in the air on the cold water pipes. M. Vitousek of the University of Hawaii carried out demonstrations and determined that strawberries and other spring crops and flowers could be grown throughout the year in the tropics using this method (see Ref. 15).

Energy Carriers

Even though the most common scenario is for OTEC energy to be converted to electricity and delivered directly to consumers, energy storage has been considered as an alternative, particularly in applications involving floating plants moored far offshore. Storage would also allow the export of OTEC energy to industrialized regions outside of the tropics. Long-term proposals have included the production of hydrogen gas via electrolysis, ammonia synthesis, and the development of shore-based mariculture systems or floating OTEC plantships as ocean-going farms. Such farms would cultivate marine biomass, for example, in the form of fast-growing kelp that could be converted thermochemically into fuel and chemical co-products or burned directly to produce heat.

Environmental Enhancement

In the very long term, there are also prospects for environmental enhancement. Should a large number of floating OTEC plantships be placed at a few strategic sites around the equatorial belt, maintaining an effective surface ocean temperature below 26.2°C, there are prospects that hurricanes and typhoons may be prevented or ameliorated (16). A similar environmental benefit could accrue toward reversing global warming through intelligent management of the upwelled water, although early computer models have shown that iron supplementation may be necessary (17).

BIBLIOGRAPHY

1. T. R. Penney and D. Bharathan, Power from the sea, *Sci. Amer.,* **256** (1): 86–92, 1987.
2. H. V. Sverdrup, M. W. Johnson, and P. H. Fleming, *The Oceans: Their Physics, Chemistry, and General Biology,* New York: Prentice-Hall, 1942.
3. C. H. Marston, Development of the adjustable proportion fluid mixture cycle, *Mech. Eng.,* **114** (9): 76–81, 1992.
4. H. Uehara and Y. Ikegami, Parametric performance analysis of OTEC using Kalina cycle, *Proc. ASME Joint Solar Eng. Conf.,* pp. 203–207, 1993.
5. L. A. Vega and D. E. Evans, Operation of a small open cycle ocean thermal energy conversion experimental facility, *Proc. Oceanology,* **94**: 5, 1994.
6. T. R. Penney, Composite turbine blade design options for Claude (open) cycle OTEC power systems. *Proc. 5th Int. Symp. Exhibition OMAE,* pp. 13–22, 1986.
7. K. J. Beck, Ocean thermal gradient hydraulic power plant, *Science,* **189**: 293, 1977.
8. C. B. Panchal and K. J. Bell, Simultaneous production of desalinated water and power using a hybrid cycle OTEC plant, *J. Solar Energy Eng.,* **109**: 156–160, 1987.
9. L. A. Vega and G. C. Nihous, Design of a 5 MW OTEC pre-commercial plant, *Proc. Oceanology,* **94**: 5, 1994.
10. G. C. Nihous, M. A. Syed, and L. A. Vega, Conceptual design of an open-cycle OTEC plant for the production of electricity and

freshwater in a Pacific island, *Proc. Int. Conf. Ocean Energy Recovery,* 1989.

11. L. A. Vega, Economics of ocean thermal energy conversion. In R. J. Seymour (ed.), *Ocean Energy Recovery: The State of the Art,* New York: American Society of Civil Engineers, 1992.
12. P. K. Takahashi and A. Trenka, *Ocean Thermal Energy Conversions; UNESCO Energy Engineering Series,* London: Wiley, 1996.
13. P. Helfrich et al., *A Preliminary Assessment of the Feasibility of Employing Ocean Thermal Energy Conversion Technology on Kiritimati (Christmas) Island in the Republic of Kiribati.* Technical Report for the Pacific International Center for High Technology Research. Honolulu: PICHTR, 1990.
14. O. A. S. Roels, M. F. Laurence, and W. Van Hemelryck, Organic production potential of artificial upwelling marine environment, *Limnol. Oceanogr.,* **13**: 18–23, 1978.
15. J. P. Craven, Keahole Point as a precursor model of government-industry-academic ocean enterprise, *The Ocean Enterprise Concept; Report on the Ocean Enterprise Workshop,* Washington, DC: National Science Foundation Office of Engineering Infrastructure and Development, 1989.
16. P. K. Takahashi et al., Marine macrobiotechnology systems, *J. Marine Biotechnol.,* **1** (1): 9–15, 1993.
17. P. K. Takahashi, Project blue revolution, *J. Energy Eng.,* **122** (3): 114–124, 1996.

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