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Ocean Energy - Status and Technology

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OCEAN ENERGY - STATUS AND TECHNOLOGY

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Introduction

The oceans occupy nearly three-quarters of our planet's surface and represent an enormous source of nonpolluting, inexhaustible energy. They provide a renewable energy resource that can be developed to reduce our reliance on fossil fuels and the resultant environmental problems of pollution and global warming. The major attraction of ocean energy development is the combination of largely benign effects on the environment and the virtually unlimited life of the resource base.

While many of the world's industrialized nations have conducted exploratory research and development on ocean energy, the total power currently available, with the exception of the French tidal power plant, is less than one hundred megawatts. With the potential energy available from the oceans far exceeding the projected global energy consumption in the future, an increasing number of tidal, wave, and thermal differential energy conversion systems are approaching an acceptable stage of development for commercial utilization. Since the majority of research funding to date has been directed toward the development of ocean thermal energy conversion (OTEC) systems and their enormous potential, our focus is on OTEC and the latest information available concerning these systems.

1. Ocean Thermal Energy Conversion (OTEC)

Solar energy is absorbed and stored as heat in the surface layer of the ocean. The OTEC process uses the temperature difference between warm surface water and cold water found at depths of 1000 meters (3280 feet) to convert thermal energy to mechanical energy for the generation of electricity. When the warm water and cold water temperature differ by at least 20° Celsius, an OTEC system can produce net power. Tropical regions, bounded by 20 degrees north and south latitudes worldwide, have a temperature difference of 20° Celsius or greater throughout the year (Figure 1).

Most of the development has focused on electrical power production; however, secondary products from OTEC systems, including transportation fuel from marine biomass, can improve their cost competitiveness. Research and development efforts have identified several applications for the cold, nutrient-rich and pathogen-free seawater in addition to the generation of electricity. Small-scale OTEC systems providing electrical power, fresh water, and nutrients for mariculture are ideal for expanding the economic potential of many island and coastal communities. The construction and operation of these systems would enable the technology to mature, strengthen commercial utility, and provide valuable experience for larger projects in the future (Takahashi et al., 1992).

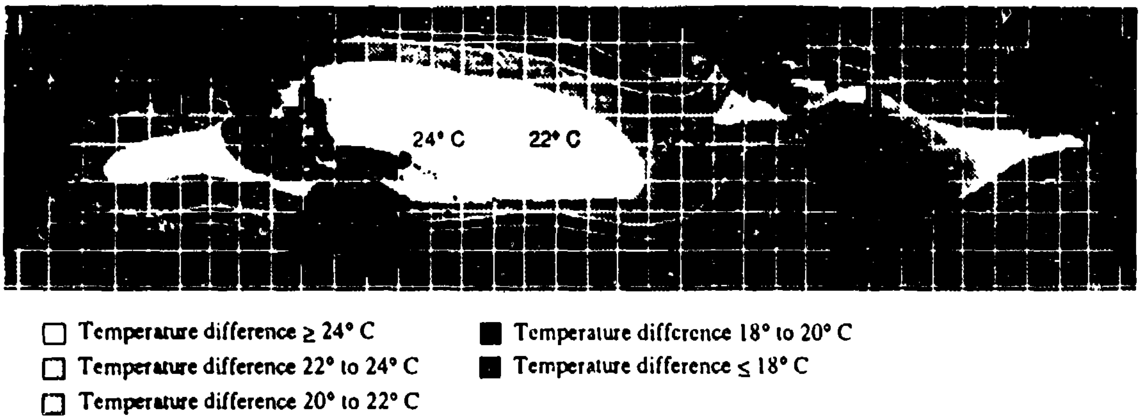

Figure 1. Temperature difference between the surface of the ocean and deep water in tropical regions

1.1 History of OTEC

The concept of ocean thermal energy conversion was first proposed by the French engineer Jacques Arsene d'Arsonval more than a century ago. He envisioned a closed-cycle heat engine using ammonia as the working fluid, but he never tested the concept. Almost fifty years passed before one of d'Arsonval's students, Georges Claude, designed and field-tested an experimental system at Matanzas Bay in northern Cuba in 1930. Although his model generated twenty-two kilowatts (kW) of power, it consumed more power than it generated. Claude later attempted a floating plant aboard a cargo vessel moored off the coast of Brazil. Waves destroyed the cold water pipe as it was being deployed, and Claude never achieved his goal of generating net power with an OTEC system (Penny and Bharathan, 1987).

A French team designed a three megawatt (MW) plant for the west coast of Africa in 1956, but the plant was never constructed. A private consulting engineer, J. Hilbert Anderson, and his son began a serious design analysis of OTEC in the 1960s. William E. Heronemus of the University of Massachusetts and Clarence Zener of Carnegie-Mellon University joined them in the early 1970s. The National Science Foundation awarded a grant to the University of Massachusetts in 1972 to assess the technical and economic feasibility of the OTEC process. They awarded another grant the following year to Carnegie-Mellon to investigate other elements of the OTEC system (Committee on Alternate Energy Sources, 1975).

When the oil embargo of 1973 prompted an international search for alternative sources of energy, the potential of OTEC was reexamined. In 1979 a closed-cycle Mini-OTEC plant produced net power, and closed-cycle heat exchangers were tested by a vessel designated as OTEC-1 in 1980 (Table 1). Both projects were conducted in Hawaii.

Table 1. OTEC Development Projects (Vadus et al., 1991)

Country	Location	Year	Size (kw)	Type Cycle	Comments
USA	Hawaii	1979	50	Closed	Mini-OTEC (Built & Tested)
USA	Hawaii	1981	1,000	Closed	OTEC-1 (Thermal Exch Test Only)
USA	Hawaii	1984	40,000	Closed	Proposed (inactive)
USA/UK/CAN	Hawaii	1991	180	Closed	Planned
USA	Hawaii	1993	165	Open	Experimental (DOE)
Japan	Nauru	1981	100	Closed	Built & Tested
Japan	Kyushu	1982	25	Closed	Built & Tested
Japan	Tokunoshima	1982	50	Closed	Built & Tested
Japan	Univ of Saga	1985	75	Closed	Thermal Exch Test Only
Taiwan	East Coast	1991	5,000	Closed	Proposed (Inactive)
France	Tahiti	1985	5,000	Closed/Open	Proposed (Inactive)
France	Africa	1985	3,000	Closed	Proposed (Inactive)
UK	Caribbean	1982	10,000	Closed	Proposed (Inactive)
UK	Hawaii	1989	500	Closed	Proposed (Inactive)
Sweden	Jamica	1983	1,000	Closed	Proposed (Inactive)
Netherlands	Bali	1982	250	Closed	Started (Inactive)

Additional experiments at the Natural Energy Laboratory of Hawaii (NELH) on the western shoreline of the island of Hawaii showed that cold deep ocean water is rich in nutrients and relatively pathogen free. Commercial development has resulted from this work, and NELH added the Hawaii Ocean Science and Technology (HOST) Park for new enterprises to continue developing applications for the cold seawater.

In 1986 the Pacific International Center for High Technology Research (PICHTR) began an open-cycle OTEC research program. Test results on evaporator spouts, warm seawater deaeration, mist removal, condensation capacity, and other factors using apparatus for measuring heat- and mass-transfer at NELH supported the design and construction of an open-cycle net power-producing experiment (NPPE) in Hawaii. Ground-breaking for the NPPE took place in November 1991 with completion in April 1993. The NPPE generates 210 kW gross power. The program is supported by the U.S. Department of Energy and the State of Hawaii (Rogers and Trenka, 1989).

1.2 Developmental Status of OTEC

There are three basic types of OTEC cycles now under development. The closed-cycle system (Figure 2A) uses the warm surface seawater to evaporate a working fluid such as ammonia or Freon, which drives a turbine generator. After passing through the turbine, the vapor is condensed in a heat exchanger cooled by water drawn from the deep ocean. The working fluid is pumped back through the warm water heat exchanger, and the cycle is repeated continuously (National Oceanic and Atmospheric Administration, 1984).

The open-cycle system (Figure 2B) uses warm surface seawater as the working fluid. The warm water is pumped into a flash evaporator in which the pressure has been lowered by a vacuum pump to the point where the warm seawater boils at ambient temperature. The steam produced drives a low-pressure turbine to generate electricity. The steam is then condensed in a heat exchanger cooled by cold deep ocean water, producing desalinated water as a by-product (Solar Energy Research Institute, 1989).

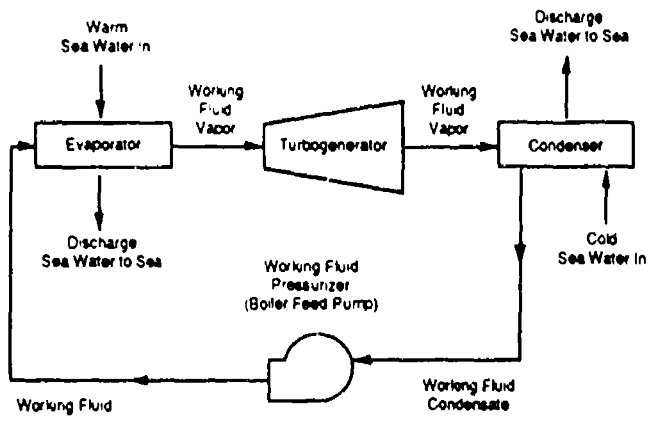

Fig. 2A. Schematic of a Closed-Cycle OTEC System

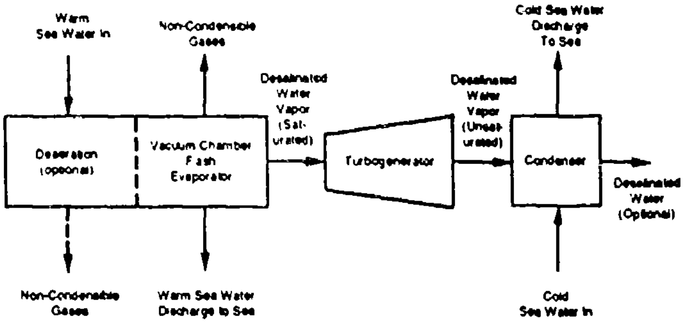

Fig. 2B. Schematic of an Open-Cycle (Claude-Cycle) OTEC System

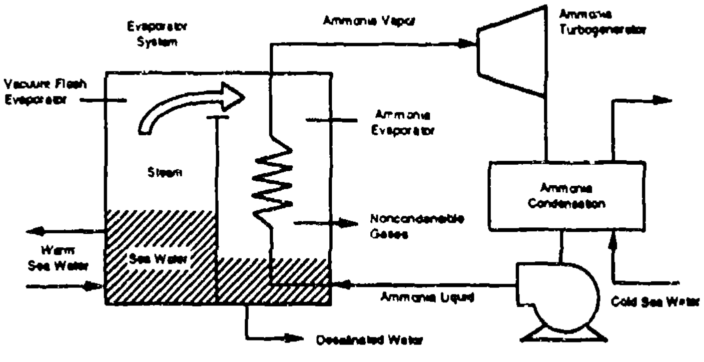

Fig. 2C. Schematic of a Hybrid-Cycle OTEC System

Figure 2. OTEC Cycles

The hybrid-cycle has not been tested, but in theory, this type of system (Figure 2C) combines the principles of the open- and closed-cycle systems, maximizing the use of the thermal resource by producing both electricity and desalinated water. First, electricity is generated in a closed-cycle stage. The temperature difference in the seawater effluent from the closed-cycle stage is sufficient to produce desalinated water by using a flash evaporator and a surface condenser in a second stage. Another possibility is the use of a second stage with an open-cycle system, which should double the output of desalinated water (Penny and Bharathan, 1987).

Early OTEC experiments focused on energy systems, but the deep ocean water, which is rich in nitrates, phosphates, and silicates, was soon identified as a resource with additional potential. For the past three years, PICHTR, with the support of the Government of Japan through the Ministry of Foreign Affairs (MOFA), has been designing a multiple-product OTEC (MP-OTEC) system (Figure 3). A multiple-product OTEC system not only generates electricity, but also provides desalinated water, air conditioning and refrigeration, and enhances mariculture and agriculture production. This type of system is important for island communities that need energy, water and food to improve their economies and quality of life.

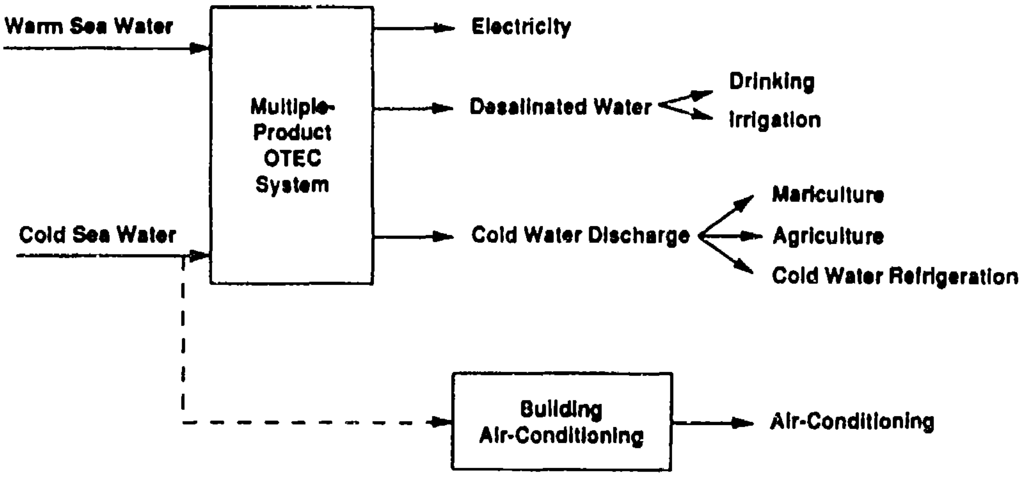

Figure 3. A multiple-product open-cycle OTEC system

A survey in 1987, initiated by PICHTR, investigated locations in the Pacific region as sites for deployment of MP-OTEC systems. Of the thirty islands and Asian locations included in the survey, PICHTR found eight locations with especially high potential: American Samoa, Western Samoa, Cook Islands, Tonga, Guam, Belau (Palau), Pohnpei, and the Commonwealth of the Northern Mariana Islands. A separate PICHTR project also assessed Kiritimati (Christmas) Island in the Republic of Kiribati as another possible location for future OTEC development.

PICHTR completed a conceptual design of a 1 MW open-cycle OTEC plant in 1989. A net power output of 1 MW corresponds to the electricity demand of many small Pacific island communities.

One megawatt OTEC plants could presently be cost-competitive in remote, oil-dependent Pacific island countries. Fuel costs currently amount to more than half the total income from imports in these areas. The levelized cost of electricity from a 1 MW OTEC plant over a 30 year period is estimated at $0.11 to $0.19/kilowatt-hour. Since the cost of electricity ranges from $0.16 to $0.44/kilowatt-hour in isolated island communities, significant savings could be realized through the use of OTEC, in addition to the other benefits offered by this technology.

The desalinated water produced by open-cycle and hybrid-cycle OTEC systems is actually less saline than the water provided by most municipal water systems. Estimates indicate a 1 MW plant fitted with a second stage fresh water production unit could supply approximately 55 kilograms/second of fresh water (4,750 m^3/day), sufficient for a population of 20,000 people. Fresh water production from reverse osmosis and multi-stage flash desalination plants costs between $1.30 and $2.00/$m^3$ for a plant with a 4,000 m^3/day capacity. Using these figures, a 1 MW OTEC plant could produce almost $3 million worth of desalinated water per year. In addition to potable, fresh water for domestic use, desalinated water from OTEC can be used for crop irrigation to increase agricultural production.

Compared with conventional air-conditioning equipment, cold seawater used to air-condition buildings can result in substantial savings. The cold seawater can circulate through space heat exchangers or can cool a working fluid circulated through heat exchangers. Research estimates that a 300 room hotel can be air-conditioned by the cold seawater from a 1 MW OTEC plant at less than 25% of the cost of electricity for operating a conventional air-conditioning system. The pay-back period for the capital investment of installing a cold seawater air-conditioning system is estimated to be four years or less. The cold water can also be used for the refrigeration of seafood and other products.

Many new strategies involving seafood and other products grown in seawater pumped from the ocean have been proposed and tested in Hawaii. OTEC-related mariculture ventures at NELH and HOST Park now represent more than 50 million U.S. dollars in capital investment. Several cold water pipes are in place, the largest which has a diameter of nearly one meter, pumping seawater from a depth of 700 meters. Current ventures include growing lobster, flat-fish, sea urchin, seaweed such as ogo and nori, and algae for chemical extracts.

A Japanese consortium built and tested a closed-cycle plant on the island of Nauru in 1981. From 1982 to the present, Japanese organizations have conducted OTEC simulations and experimental plant projects. The Kochi

Artificial Upwelling Laboratory near the Murota Peninsula on Shikoku Island in Japan, features a 12.5 centimeter (5 inch) diameter cold water pipe, bringing water from 320 meter depths to the surface. Growth kinetics for marine plants and animals are being conducted. Although OTEC mariculture is still in the developmental stage, steady progress is being made. Further research and commercialization activities are needed to demonstrate its economic viability.

Researchers at the University of Hawaii were first to propose the idea of using cold seawater in agriculture. An array of cold water pipes buried in the ground creates cool weather conditions not normally found in tropical environments. The system also produces drip irrigation by atmospheric condensation on the pipes. Using this method, the growth of strawberries and other spring crops and flowers throughout the year in the tropics has been demonstrated. Commercial developers have initiated cold-water agriculture enterprises in Hawaii.

1.3 OTEC Thermodynamics

Engineering thermodynamics is a field of study concerned with transformations or exchanges of energy within a system or between a system and its surroundings. Here, the term system denotes either a fixed quantity of matter, a device, or a region in space that is being examined. Four laws constitute the basis for all engineering thermodynamics analyses. The zeroth law of thermodynamics states that any two objects in thermal equilibrium with a third object (such equilibrium being manifested by zero net heat transfer) are, in turn, in thermal equilibrium with one another. This law is invoked each time a calibrated measurement device is used to determine temperature. The third law of thermodynamics establishes an absolute datum for a property called entropy. The third law is particularly relevant to the study of chemically-reacting mixtures.

For OTEC systems, where chemical reactions generally are assumed to play an insignificant role in the power generation process, the first and second laws of thermodynamics are of primary interest to the engineer. Thermodynamic analyses typically focus on identifying the modes and amounts of energy transfers between a system and its surroundings and the assessing resulting changes in state. Once the boundaries of the system clearly are identified, an energy balance, or accounting, can be performed that the considers transfers that occur across these boundaries and changes in state taking place within them. This accounting can be summarized as (Reynolds and Perkins, 1977):

Energy production = energy outflows - energy inflows + increase in energy
within the system from the system into the system within the system

Given the practical benefits of this production bookkeeping formalism, we now offer a simple statement of the first law of thermodynamics: *The production of energy is always and everywhere equal to zero.* Energy, like mass, is a conserved quantity; it may be transferred and transformed but may not be created nor destroyed.

Figure 4 depicts a system exchanging energy with its environment by all three modes: convection, heat transfer and work. The system comprises a region in space bounded by an imaginary, closed control surface (indicated by the dotted line). If E is taken to represent the sum of all microscopic and macroscopic energy of the matter in the system at a given time, then the increase in energy within the system = dE/dt.

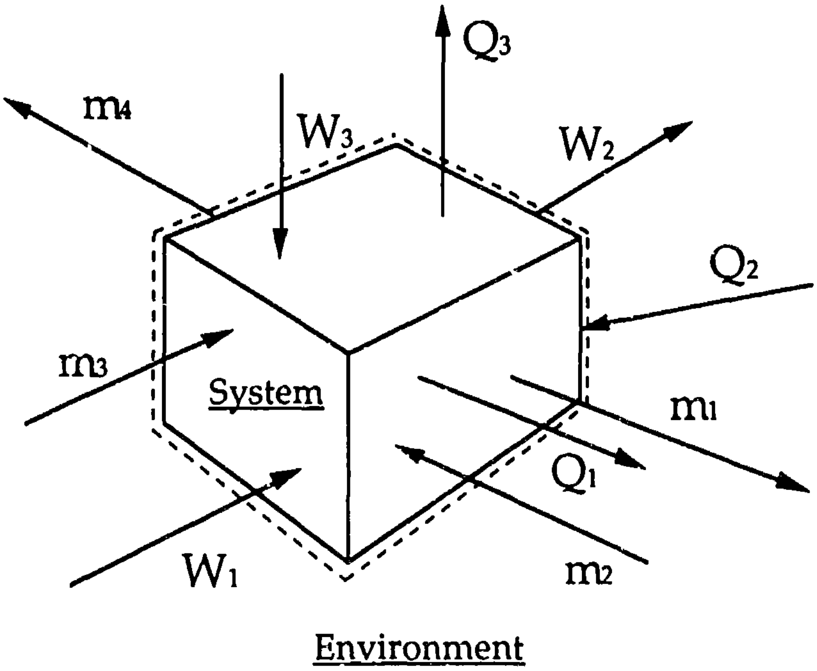

Figure 4. System exchanging energy by convection, heat transfer, and work

Although most of the development behind the preceding example has been omitted, it serves to demonstrate the rationale behind, and general form of the energy balance utilized to analyze the performance of engineering devices. Moreover, it clearly states the constraint imposed by the First Law: that, deprived of a source or sink for energy (i.e., a non-zero production term), the net exchange of energy between a system and its environment is directly related to a change in E and the state of the material within the system.

In order for an event or process to occur, an energy balance on the system of interest must satisfy the first law of thermodynamics; however, satisfying the first law is not sufficient to guarantee that a process or event is indeed feasible. Viability must be assessed by invoking the second law of thermodynamics.

In statements of the second law, the property of interest is the entropy, S. A detailed explanation of entropy is too involved to recount here. Entropy should be perceived as a property that quantifies uncertainty about the microscopic condition of matter. Specifically, it is related to the number of ways the total energy of a system may be distributed among the allowed energy states of the ensemble of constituent molecules or atoms. The more energy states accessible, the greater the uncertainty that any specific distribution will exist at a given time. Entropy increases as this uncertainty increases.

Entropy may be transferred in space by convection or heat transfer. Work interactions are not accompanied by a transfer in entropy. One way to explain this is to consider that work involves organized events that are perceived at the macroscopic level. Since entropy reflects randomness at the microscopic level, it can be argued that there can be no relationship between work and entropy. On the other hand, heat transfer occurs as a result of random collisions between molecules and atoms. The end result of these collisions is a transfer of both internal energy and entropy. It can be shown that entropy transfer proceeds at a rate given by:

$$dS/dt = Q/T\,,$$

where T is the absolute temperature at the location where heat transfer is taking place.

As in the case of energy, an accounting may be performed on entropy exchanges between a system and its environment. In production bookkeeping form, this balance may be expressed as:

Entropy production = entropy outflows - entropy inflows + increase in entropy
within the system from the system into the system within the system

In terms of production bookkeeping, the second law of thermodynamics may be stated as: *The production of entropy must always be greater than or equal to zero*, i.e., $P_S \geq 0$. Unlike energy, entropy may be created and, once created, may never be destroyed. Hence, only processes or events that conserve energy and result in non-negative entropy production are viable. If entropy production is zero, the process or event is called reversible; if greater than zero, irreversible.

For OTEC, the objective is to fabricate a system that transforms the internal energy of warm, surface seawater to electrical power which can be delivered to consumers. Since the source of energy stored in warm seawater is the sun, OTEC is a form of indirect, solar energy power conversion. A device that converts internal energy to work or power is called a heat engine. Specifically, a heat engine is a system that receives energy from its environment by heat transfer and returns energy to its environment via work.

Historically, the study of heat engines has been a primary focus of thermodynamics. One of the major results of classical thermodynamics is embodied in the Kelvin-Planck statement on the operation of heat engines. A heat engine receives energy from a thermal resource (or reservoir) by means of heat transfer. It can be shown that the second law requires that heat transfer take place from a warmer body to a cooler body. If no energy is rejected from the heat engine to its environment by heat transfer, it is referred to as a 1T (for one thermal reservoir) heat engine. If heat is rejected to a cooler thermal sink, then it is called a 2T (for two thermal reservoirs) heat engine. Figure 5 provides a sketch of 1T and 2T heat engines.

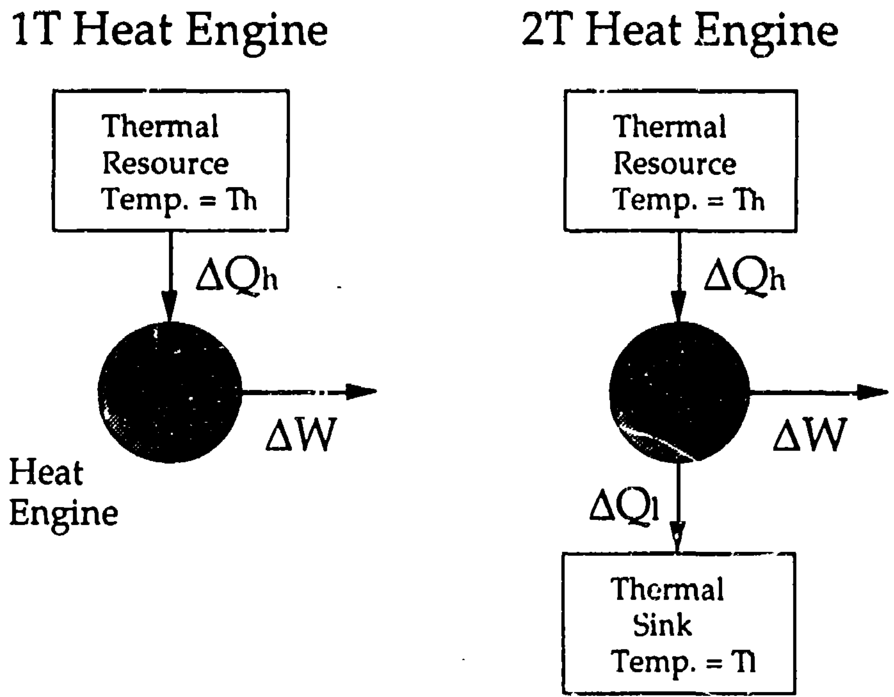

Figure 5. 1T and 2T heat engines

Typical heat engines operate cyclically. That is, the state of the material in the heat engine is the same at the beginning and the end of the power production process. This means that, over one complete cycle, the storage of energy within the system is zero. An energy balance for the heat engine, performed over one cycle, demands that either:

$0 = DW - DQ_h + 0$,(1T heat engine)

or

$0 = (DW + DQ_l) - DQ_h + 0$ (2T heat engine)

Note that the zero energy production and energy storage terms have been included for completeness. DW and DQ are the total energy transfers, which take place over the course of a cycle, between the engine and its surroundings, by work and heat, respectively. Rearranging terms we have expressions for the work produced:

$$DW = DQ_h \,; \qquad \text{(1T heat engine)}$$

or

$$DW = DQ_h - DQ_l \,. \qquad \text{(2T heat engine)}$$

For a 1T heat engine operating cyclically, all energy received from the thermal resource is converted to work. For a 2T heat engine, only a portion of this energy is converted to work, the balance being reject to the thermal sink.

The second law of thermodynamics as expressed by the Kelvin-Planck statement imposes a major constraint on the operation of a cyclic heat engine. Briefly, it states that a cyclic 1T heat engine is impossible. Based on the first law balances performed above, this means that 100% conversion of the energy extracted from a thermal resource, DQ_h, to useable work is impossible.

The first and second laws of thermodynamics may be employed to show that irreversible processes occurring during the operation of a heat engine reduce the fraction of thermal energy that ultimately is converted to work. Maximum energy conversion is obtained when entropy production by a heat engine is zero, i.e., when the engine operates reversibly. Such an ideal device is called a Carnot heat engine.

Extensive analyses of Carnot engines have been conducted to estimate the limiting performance of thermal power generation devices. A very important result relates the conversion efficiency, h, defined as

$$h = DW/DQ_h \,,$$

to the absolute temperatures (in Kelvin or Rankine) of the thermal resource, T_h, and thermal sink, T_l. It can be shown that for a 2T Carnot heat engine operating cyclically,

$$h = 1 - (T_l/T_h) \,.$$

Heat transfer between the Carnot engine and the thermal reservoirs must take place reversibly, i.e., over an infinitesimal temperature gradient. Clearly such heat transfer is impracticable in an actual device.

The high-temperature thermal source for OTEC is warm surface seawater. Even in the tropics, the temperature of this resource is not expected to exceed about 30°C or approximately 303 K. Since, from a practical standpoint, continuous, cyclic operation of the OTEC heat engine is desirable, a cooler thermal sink must be identified. As is evident in the relationship for the Carnot efficiency, h of the cycle increases as the temperature of this sink is reduced. OTEC proposes to reject heat from the power generation system (engine) to cold seawater brought up from the depths of the ocean by a pipeline. Given current practical limitations on the required pumping system, the lowest temperature accessible probably lies around 4°C or 277 K. Hence, even under the best of operating conditions, an ideal heat engine would have an energy conversion efficiency of only

$$h \,'\, 1 - (277/303) = 0.086 \text{ or } 8.6\% .$$

This means that over 90% of the thermal energy extracted from surface seawater is "wasted." This result should be compared with the Carnot efficiency of a typical state-of-the-art combustion steam power plant. Here, T_h is the supercritical boiler temperature that may be as high as 810 K, and the cooling water temperature, T_l, will hover around ambient, say 300 K. Hence,

$$h \,'\, 1 - (300/810) = 0.63 \text{ or } 63\% .$$

While power cycles based on the combustion of fossil fuel enjoy significantly higher theoretical conversion efficiencies, the resource employed is limited and undesirable by-products of the process, specifically, combustion gas pollutant species may damage the environment. OTEC, on the other hand, consumes, albeit relatively inefficiently, a resource that is constantly being renewed by the sun, and may be configured in a way that poses little threat to the environment.

It must be pointed out that the Carnot efficiency calculated above applies to an ideal, reversible cycle that exchanges heat with its surroundings over an infinitesimally small temperature gradient. An actual OTEC heat engine will transfer heat irreversibly and produce entropy at various points in the cycle. This will reduce further the fraction of energy extracted from the warm seawater that ultimately is converted to electrical power.

The basic, ideal Rankine cycle comprises four major steps: (1) isentropic compression (pumping) of a liquid; (2) constant pressure heat transfer from the thermal resource resulting in vaporization of the liquid; (3) isentropic expansion of the vapor through a turbine to generate power; and (4) constant pressure heat transfer to the thermal sink resulting in complete condensation of the working fluid. The heat exchangers employed in steps (2) and (4) usually are called boilers and condensers, respectively.

A process representation for the ideal Rankine cycle, which depicts the changes in state of the working fluid as it progresses through the different steps, is shown in Figure 6. Following conventional engineering practice, the process has been plotted on the T-S (temperature-entropy) property plane of a hypothetical working fluid. The bell-shaped curve in the figure is known as the vapor dome. The vapor dome separates the liquid and vapor (gas) states of the fluid: points to the left of the dome are liquid, to the right, vapor, and within its borders, a mixture of saturated liquid and saturated gas (saturation implies boiling conditions). The segmented lines that horizontally cross the vapor dome are isobars, i.e., lines of constant pressure in the T-S plane.

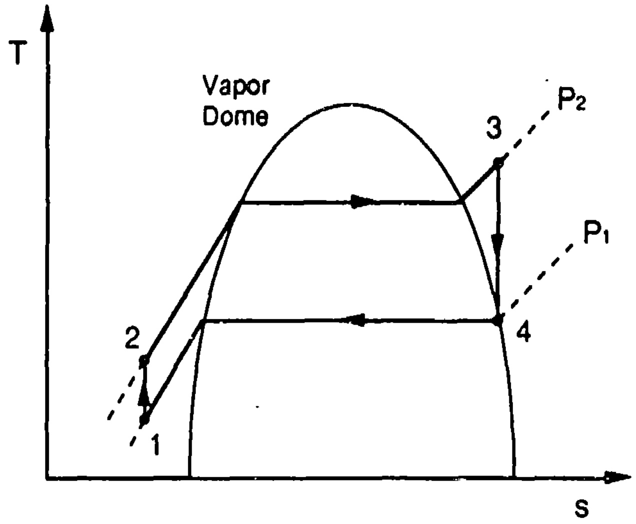

Figure 6. Ideal Rankine cycle process representation

A schematic diagram showing the major components used in a Rankine cycle is given in Figure 7. These four components include a pump, boiler, turbine, and condenser. State points marked on Figure 7 correspond to the numbers on the process representation.

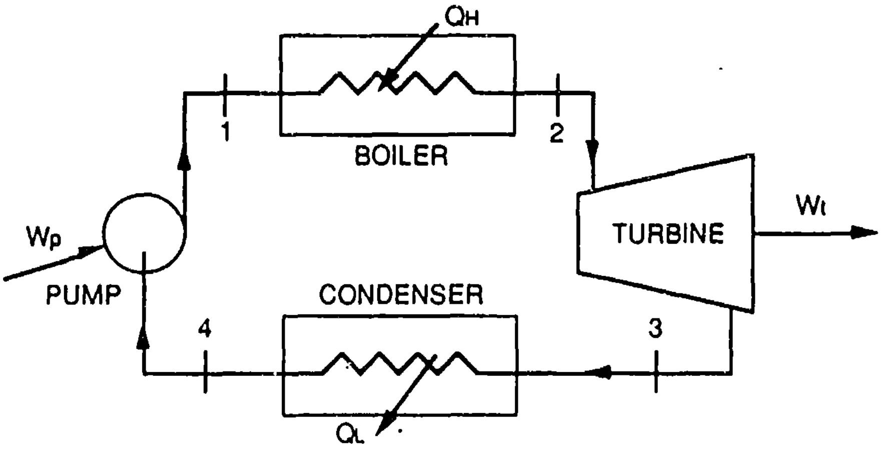

Figure 7. Rankine cycle components

In an actual Rankine heat engine, pressure drops occur in the boiler and condenser, and irreversibilities in the turbomachinery result in increases in the entropy of the working fluid passing through these devices. Referring to the definitions of component efficiencies, it can be shown that these effects increase the power consumed by the pumps and decrease the power generated by the turbine for each unit of energy received from the thermal resource. Net power output to the environment, i.e., the difference between power generated and power consumed by cycle parasitics, decreases along with cycle efficiency.

Rankine cycles are able, in theory, to produce non-zero net power, largely due to the fact that significantly less energy is required to increase the pressure of a liquid from some P_1 to P_2, than can be recovered as work when the same fluid expands as a vapor from the same P_2 back to P_1. Hence, the phase changes in the boiler and condenser are of critical importance to Rankine cycle operation.

In conventional steam power stations, the thermal resource is provided either by combusting a fossil fuel or through nuclear fission. Water from a river, ocean, or large, artificial reservoir assumes the role of the thermal sink. Following the example of the Carnot 2T heat engine, the Rankine cycle is designed so that the working fluid, water, receives energy at as high an average temperature as practically possible, and rejects it at a temperature as close to that of the sink as the effectiveness of the condenser allows. Since saturation temperature varies directly with pressure, this requires that boiler pressures exceed atmospheric and that the steam side of the condenser operates at partial vacuum. High pressures and temperatures require heavy and expensive piping and components, while the in-leakage of air or coolant must be carefully guarded against at locations in the system where working fluid pressure drops below atmospheric. These practical considerations limit the efficiencies of steam power stations.

When the Rankine cycle is applied to the OTEC resource, where the difference in source and sink temperatures rarely exceed 40° F or 22° C, compared with up to 3600° F or 2000° C in combustion-driven systems, a different strategy must be applied. The major change is the substitution of a working fluid that boils and condenses at significantly lower temperatures than water at the same pressure. Factors that influence the selection of the working fluid include: (1) cost and availability, (2) compatibility with materials employed in piping, conventional turbomachinery components, and heat exchangers, (3) toxicity, and (4) environmental hazard.

To date, the leading candidates for the working fluid of closed-cycle OTEC plants are ammonia and several types of CFCs. Ammonia and CFCs are used extensively in refrigeration systems, which operate as Rankine cycles run in reverse, and also have been employed as working fluids in (relatively) low-temperature geothermal power plants. Their primary disadvantage is the environmental hazard posed by leakage of these substances. Ammonia is toxic in moderate concentrations and many types of CFCs attack and destroy the ozone layer of the atmosphere.

1.4 OTEC Technology

To understand the details of operation of closed-cycle OTEC, it is useful to consider a specific example. Figure 8 presents a flow diagram of a Rankine cycle plant employing ammonia as a working fluid. Table 2 summarizes the operation of a small, pre-commercial closed-cycle test plant designed to produce approximately 500 kW at the terminals of the electric generator driven by the turbine. Although a megawatt-size, commercial OTEC power system will enjoy certain economies of scale, the present example is not unrepresentative of anticipated performance.

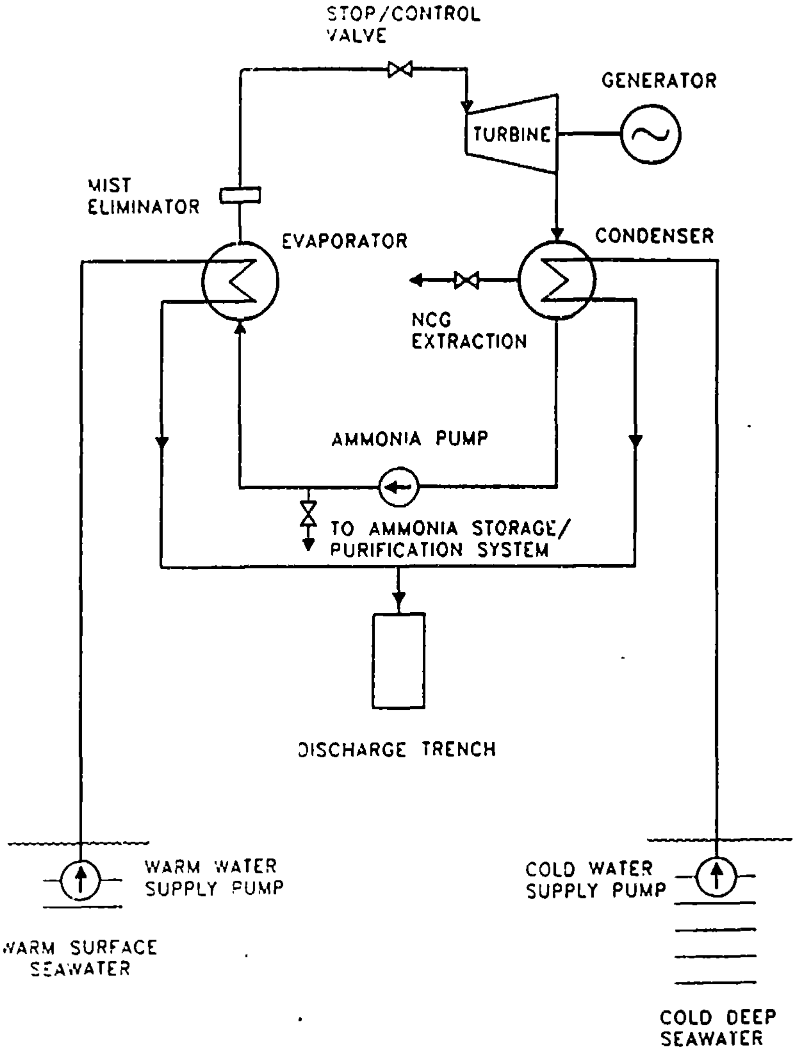

Figure 8. Closed-cycle OTEC flow diagram

Table 2. Closed-cycle OTEC system summary

Warm water pipe outer diameter = 1.6 meters (63 inches)
Cold water pipe outer diameter = 1.0 meter (40 inches)
Discharge pipe outer diameter = 1.6 meters (63 inches)
Cold water pipe intake depth = 1,000 meters (3,280 feet)

Gross power = 497 kW
Net power = 272 kW

Warm water flow = 1.34 m^3/s (21,200 gpm)
Cold water flow = 0.86 m^3/s (13,600 gpm)

Warm water supply temperature = 26.5 °C (79.7 °F)
Cold water supply temperature = 4.7 °C (40.4 °F)
Warm water return temperature = 22.8 °C (73.0 °F)
Cold water return temperature = 10.3 °C (50.6 °F)

Turbine inlet temperature = 21.2 °C (70.2 °F)
Turbine inlet pressure = 892,000 Pa (130 psia)
Turbine outlet temperature = 11.7 °C (53.1 °F)
Turbine outlet pressure = 653,000 Pa (95 psia)

Hydraulic loss in evaporator = 2.5 meters (8.23 feet)
Hydraulic loss in condenser = 2.6 meters (8.63 feet)

Cold water pipe friction loss = 4.5 meters (14.75 feet)
Cold water pipe density head loss = 0.5 meters (1.58 feet)

Warm water pipe friction loss = 0.6 meters (1.93 feet)
Mixed discharge pipe friction loss = 0.8 meters (2.68 feet)
Discharge trench water level = 0.9 m above mean sea level

Warm water pump power = 99.3 kW
Cold water pump power = 114.6 kW
Ammonia pump power = 10.7 kW

The closed-cycle OTEC system is identical to a simple Rankine steam power plant with the exception of the working fluid and the high-temperature thermal source. In the 500 kW closed-cycle plant, warm surface seawater is pumped into the evaporator where heat transfer occurs to pressurized liquid ammonia. The pressure of the liquid ammonia (130 psia) is selected to ensure that boiling takes place several degrees below the temperature of the warm seawater. This accommodates the anticipated non-unity effectiveness of the evaporator. Ammonia vapor exiting the evaporator passes through a series of stop and control valves before entering the turbine. The vapor then expands through the turbine, turning a rotor connected to an electric generator.

Ammonia vapor pressure at the outlet to the turbine corresponds to a saturation (condensation) temperature about 7 °C higher than the temperature of the cold seawater. Cold seawater is brought up from a depth of 1000 meters and is pumped into the condenser where the ammonia vapor changes to liquid. This liquid ammonia then is pressurized by a pump and the cycle is repeated. Provisions to extract and purify the ammonia circulating in the power loop are included along with a mixed discharge trench to collect and return the seawater effluent from the heat exchangers to the ocean.

It should be noted that the seawater pumps shown were sized assuming a land-based power plant utilizing bottom-mounted, submerged pipelines. As demonstrated in the preceding chapter, a significant fraction of the power consumed by these pumps is expended to overcome friction in these pipelines. This loss scales with the length of the pipes and, hence, depends strongly on the bathymetry offshore of the plant. A gently-sloping ocean floor will require a longer length of pipe to reach the required depth (i.e., access the desired sink temperature), incurring high power losses. The performance of land-based OTEC plants therefore varies with location. Floating plants, which mount power generating equipment on offshore barges, have been proposed to minimize this site-dependence. In floating plants, pipelines extend vertically downward.

In the present example, T_h = 79.7° F (539.4 R) and T_l = 40.4° F (500.1 R); a Carnot 2T heat engine therefore could attain a power conversion efficiency of 7.29%. Using typical values of efficiencies of commercially-available equipment (e.g., h_{turb} = 80%; h_{pump} (ammonia) = 75%), the detailed thermodynamic cycle analysis summarized in Table 2 reveals that the efficiency of the real system, not including the seawater pumping losses, is about 2.5%. Subtracting seawater pumping losses from the power generated by the turbine reduces the overall net efficiency to only 1.4%.

The Claude or open-cycle proposes to use steam generated from the warm seawater as the working fluid. The steps of this cycle are: (1) flash evaporation of a fraction of the warm liquid by reduction of pressure below the saturation value corresponding to its temperature; this step may perceived as heat transfer from the bulk of the liquid to the portion vaporized; (2) expansion of the vapor through a turbine to generate power; (3) heat transfer to the cold seawater thermal sink resulting in condensation of the working fluid; and (4) compression of the condensate and any residual non-condensible gases to pressures required to discharge them from the power generating system. It is clear that the Claude cycle is very similar to the Rankine cycle with the exception that the state of the effluent at the end of step (4) need not match the state of the fraction of mass of the warm seawater that becomes the working fluid at the start of step (1).

Flash evaporation is a distinguishing feature of open-cycle OTEC. Flash evaporation involves complex heat and mass transfer processes. In the configuration most frequently proposed for open cycle OTEC evaporators, warm seawater is pumped into a chamber through spouts designed to maximize heat and mass transfer surface area by producing a spray of the liquid. The pressure in the chamber is less than the saturation pressure of the warm seawater. Exposed to this low-pressure environment, water in the spray begins to boil. As in thermal desalination plants, the vapor produced is relatively pure steam. As steam is generated, it carries away with it its heat of vaporization. This energy comes from the liquid phase and results in a lowering of the liquid temperature and the cessation of boiling. Thus, as mentioned above, flash evaporation may be seen as a transfer of thermal energy from the bulk of the warm seawater to the small fraction of mass that is vaporized to become the working fluid. It is estimated that less than 0.5% of the mass of warm seawater entering the evaporator is converted into steam.

At 79.7° F (26.5° C), the approximate temperature of warm seawater, the saturation pressure, P_{sat}, of pure water is only 0.50 psia (3464 Pascal). At a cold seawater temperature of, say, 40.4° F (4.7° C), saturation pressure is 0.12 psia (852 Pascal). These two values of P_{sat} establish the approximate operating pressure range of an ideal, open-cycle OTEC system. Frictional pressure drops and non-ideal heat exchanger effectiveness will reduce this range in an actual plant. It is clear, however, that the evaporator, turbine, and condenser will operate in partial vacuum. This poses a number of practical concerns that must be addressed.

First, the system must be carefully sealed to prevent in-leakage of atmospheric air that can degrade severely or shut down operation. Second, the specific volume of the low-pressure steam is very large compared to that of the pressurized working fluid used in closed-cycle OTEC. This means that components must have large flow areas to ensure that steam velocities do not attain excessively high values. Finally, gases such as nitrogen and carbon dioxide that are dissolved in seawater come out of solution in a vacuum. These gases will flow through the system with the steam but will not be condensed in the condenser. Since pressurization of a gas requires considerably more power than pressurization of a liquid, these non-condensible species increase the parasitic loss associated with the discharge step (4) of the process.

In spite of the aforementioned complications, the Claude cycle enjoys certain benefits from the selection of water as the working fluid. Water, unlike ammonia or CFCs, is non-toxic and environmentally benign. Moreover, since the evaporator produces desalinated steam, the condenser can be designed to yield a flow of potable, fresh water. In many potential OTEC sites in the tropics, potable water is a highly desired commodity that can be marketed to offset the price of OTEC-generated electricity.

A large turbine is required to accommodate the huge volumetric flow rates of low-pressure steam needed to generate any practical amount of electrical power. Although the last stages of turbines used in conventional steam power stations can be adapted to open-cycle OTEC operating conditions, it is widely accepted that existing technology limits the power that can be generated by a single open-cycle OTEC turbine module, comprising a pair of rotors, to about 4 MW. Unless significant effort is invested to develop new, specialized turbines (which may employ fiber-reinforced plastic blades in rotors having diameters in excess of 100 meters), increasing the gross power generating capacity of a Claude cycle plant above 4 MW will require multiple modules and incur an associated equipment cost penalty.

Condensation of the low-pressure working fluid leaving the turbine occurs by heat transfer to the cold seawater. This heat transfer may occur in a direct-contact condenser (DCC), in which the seawater is sprayed directly over the vapor, or in a conventional shell-and-tube or plate-and-shell surface condenser that does not allow contact between the coolant and the condensate. DCCs have been proposed since they are relatively inexpensive and have good heat transfer characteristics due to the lack of a solid thermal boundary between the warm and cool fluids. Although surface condensers for OTEC applications may be expensive to fabricate and, possibly, difficult to maintain, they do permit the production of fresh water. Fresh water production is impossible with a DCC unless fresh water is substituted for seawater as the coolant in the DCC. In such an arrangement, the cold seawater sink is used to chill the fresh water coolant supply using a liquid/liquid heat exchanger.

Effluent from the low-pressure condenser must be returned to the environment. Liquid can be pressurized to ambient conditions at the point of discharge by means of a pump or, if the elevation of the condenser is suitably high, it can be compressed hydrostatically. Non-condensible gases, which include any residual water vapor, dissolved gases that have come out of solution, and air that may have leaked into the system, must be pressurized with a compressor. Although the primary role of the compressor is to discharge exhaust gases, it usually is perceived as the means to reduce pressure in the system below atmospheric. As mentioned earlier, for a system that includes both the OTEC heat engine and its environment, the cycle is closed and parallels the Rankine cycle. Here, the role of the Rankine cycle pump is assumed by the condensate discharge pump and the non-condensible gas compressor.

A hypothetical commercial open-cycle OTEC plant that produces about 1.1 MW of net electrical power and 1.26 million gallons/day of potable water was designed to accommodate the needs of a small community on a developing Pacific island. A separate stage that utilizes the seawater effluent from the power generation system evaporator and surface condenser has been included to maximize fresh water production. This stage comprises a second flash evaporator and surface condenser only (no turbine). Such a fresh water production system could, in principle, be added to a closed-cycle plant to generate some fresh water.

Warm seawater at 26°C is discharged through spouts in a flash evaporation chamber maintained at approximately 2740 Pascal. At this pressure, the seawater is about 3.4° C superheated. Calculations indicate that out of 6156 kilograms/second of seawater, only 27.4 kilograms/second of steam, 0.45% by mass, is produced. Transfer of the latent heat of vaporization to the steam results in a 2.7° C drop in the temperature of the seawater. The mixture of saturated steam and trace quantities of dissolved gases passes through a mist eliminator installed to remove tiny droplets of seawater entrained by the working fluid. The steam then passes through a single-stage, single-flow, axial turbine coupled to an electric generator. The turbine selected is a modified L-0 (last row) stage used in large nuclear power stations. The diameter of the rotor is 5.65 meters.

Although a diffuser is employed downstream of the rotor exit, care must be exercised not to expand to too low a pressure. Since in open-cycle OTEC, the working fluid will enter the turbine as either a saturated or very slightly superheated vapor (due to a small pressure drop between the evaporator and turbine), some condensation can, and probably will, occur as this vapor expands to a lower pressure. Liquid droplets mixed with the steam will erode the rotor blades and degrade aerodynamic performance of the turbomachine.

After exiting the turbine diffuser the pressure of the working fluid is 1290 Pascals, which corresponds to a condensation temperature of 10.7° C. Heat transfer to the 4° C cold seawater occurs in a surface condenser producing 26.6 kilograms/second of fresh water. Calculations indicate that about 3% of the water vapor will not be condensed. Finally, the non-condensible gases are removed from the system and are exhausted to the atmosphere by a vacuum compressor train that employs intercoolers to approximate the more efficient isothermal compression process. While a closed-cycle system will employ valves to throttle mass flow into the turbine and control its operation, it has been proposed that the compressor be used to perform this function in an open-cycle plant. Changing the rate at which non-condensibles are removed by the compressor from the power generation loop will alter pressures in the system which, in turn, will affect steam production and applied torque (by the steam) to the turbine rotor. This strategy eliminates the fluid friction loss arising from control valves mounted in the steam path.

While open-cycle OTEC plants may be mounted on offshore barges, means will have to be devised to transport both electricity and fresh water to shore. In the present example, the Carnot power conversion efficiency corresponding to $T_h = 26°$ C (299.15 K) and $T_l = 4°$ C (277.15 K) is 7.35%. Thermodynamic analysis of the actual proposed cycle yields an efficiency of about 2.5%, if the seawater pumping losses are omitted, and about 1.6% if these losses are subtracted from the electrical power generated. Although there is a four-fold difference in the scale of the two example facilities and a second stage for water production has been included in the open-cycle system design, the performance results are quite similar.

The open and closed OTEC cycles are strategies to operate 2T heat engines that exploit the thermal gradient of tropical oceans to produce electric power. The small temperature difference between the proposed thermal source and sink limit maximum power conversion efficiency to about 7%. Irreversibilities in real devices and systems, and external parasitic losses associated with pumping the large volumes of seawater required to sustain operation, make operation at more than about 2% efficiency highly unlikely. Thermal performance of the two cycles is not expected to differ significantly for similar size plants. In spite of its low efficiency, OTEC can be a viable alternative to conventional power generation methods since the energy resource it consumes is renewable and undesirable byproducts are few.

The principal differences between open- and closed-cycle OTEC lie in the choice of working fluid. Closed-cycle systems propose to employ ammonia, CFCs, or some other high-pressure, low boiling point substance. Open cycle OTEC uses low-pressure steam evaporated from the warm seawater. Because of its significantly higher operating pressures and, hence, lower volumetric flow rates, closed-cycle systems may employ compact components to produce the same amount of power as open-cycle systems. Assuming that means will be available efficiently to supply the required warm and cold seawater, closed-cycle plants can be designed to produce tens of megawatts of net electrical power using existing turbomachinery and heat exchanger designs. On the other hand, practicable open-cycle OTEC systems with capacities in excess of a few megawatts probably will require a significant turbine development effort.

Although open-cycle OTEC plants suffer from large size and practical limitations on maximum power generation capacity, the working fluid employed poses no environmental hazard. Moreover, potable water produced in the condenser may be sold as a commodity to offset the cost of the OTEC-generated electricity. The selection of either an open or closed OTEC cycle for a particular application will depend on the desired electrical capacity and the relative importance of power and potable water. Beyond a certain point, this decision probably will be driven by economic, rather than technical factors.

To date, the majority of designs submitted for commercial OTEC systems propose to utilize modified versions of components found in conventional fossil fuel or geothermal electric power stations. These components include heat exchangers and turbomachinery such as compressors, turbines, and pumps. A review of means applied to assess the performance of these devices therefore is warranted.

Analyses and discussions of the detailed fluid mechanics and heat transfer processes occurring within the devices of interest will be avoided. Rather, performance will be quantified by means of global parameters such as isentropic or isothermal efficiencies and heat exchanger effectiveness. Although such an approach ignores the important physics of the operation of these devices, and restricts the level and extent of analysis possible, it is simple to apply and probably sufficient for the present purposes.

Efficiencies and effectiveness are parameters that compare the ability of an actual device to perform a given task under specific operating conditions to the best theoretical performance possible by an ideal device (operating under the same conditions) that produces a minimum of entropy. Since methods to conduct thermodynamic analyses of ideal devices have been developed and are relatively simple to use, these global parameters afford a convenient means to assess the performance of power generation equipment. Values, charts, or equations for efficiencies and effectiveness are provided by manufacturers of devices to system integrators and analysts.

It has been suggested previously that the performance of an energy-related task will proceed most efficiently when all steps undertaken are reversible. This is reasonable if we accept that irreversibilities, i.e., events or processes that produce entropy, degrade transfers or transformations of energy. Common sources of irreversibilities include friction (which manifests itself by the transformation of some organized, macroscopic motion, to random, molecule motion, i.e., heating), mixing of different chemical species, heat transfer across a finite temperature difference, and spontaneous chemical reaction.

The three classes of turbomachinery that have been proposed for use in OTEC systems are pumps, turbines and compressors. Pumps and compressors transform external power into an increase in fluid pressure. Pumps are used when the fluid is a liquid, compressors when the fluid is a gas. Turbines operate in reverse of pumps and compressors: they are designed to transform the internal energy of a working fluid, with a resultant pressure drop, into power that can be exported to the surroundings.

A major objective of pump and compressor design is to minimize power consumption for a given rise in fluid pressure. Hence, efficiencies compare the energy consumed by real and ideal devices operating between the same inlet fluid state and exit pressure, and handling the same mass flow rate. If the inlet state is denoted as 1 and the exit as 2 or 2s, where the s indicates that the desired pressure increase has occurred isentropically, then it can be shown that

$$h_{pump} = h_{comp} = W_s/W_{real} = (h_{2s} - h_1)/(h_2 - h_1) ,$$

where h_i is the enthalpy of the fluid at state i. These isentropic efficiencies will assume values that lie between 0 and 1. This expression has been derived assuming steady operation of the pump or compressor, negligible changes in kinetic and potential energy of the fluid, equilibrium at the inlet and outlet, and zero heat transfer between the fluid and the environment while passing through the device.

Although the theoretical basis of the relationship given above for h_{comp} is sound, it is found that the power consumed for a given compression ratio actually is minimized when the entropy production is zero and the temperature of the fluid remains constant. Such an ideal, isothermal compression process can only occur if heat transfer takes place reversibly from the fluid to the environment during the course of the compression. An isothermal compressor efficiency, similar in form to the isentropic efficiency given above, often is employed as an alternative performance parameter. In real systems, intercoolers frequently are used between compressor stages to approximate isothermal compression.

As expected, since maximizing power output for a given pressure drop is the primary objective of turbine design, the isentropic efficiency is defined as the inverse of the pump/compressor efficiency:

$$h_{turb} = W_{real}/W_s = (h_2 - h_1)/(h_{2s} - h_1) ,$$

where, again, 1 and 2 or 2s denote the states at the inlet and exit of the turbine, respectively. The assumptions underlying the above expression are identical to those used to analyze the pump and compressor. This isentropic turbine efficiency compares the performance of the actual and ideal turbine operating between the same inlet state and exit pressure. Note that since W_{real} is always $\leq W_s$, $0 \leq h_{turb} \leq 1$.

Heat transfer losses, fluid turbulence, and friction (viscous shear) in boundary layers reduce the isentropic efficiencies of turbomachinery components below the theoretical limit of 100%. Efficiencies of state-of-the-art, industrial turbines may attain values as high as about 90%; isentropic efficiencies of large, axial and centrifugal compressors range between 70% and 85% while hydraulic pump efficiency rarely exceeds 65%.

Heat exchangers are devices employed to facilitate the exchange of energy, typically from one fluid to another, by heat transfer. Two major classes of these devices exist: (1) heat exchangers in which the fluids are separated by a solid boundary; (2) direct-contact devices in which the hot and cold fluid streams are allowed to mix.

Heat exchanger design focuses on maximizing the amount of thermal energy transferred between two fluid streams entering at a given pair of temperatures (or states). Practical objectives include minimizing the pressure drop size, complexity, and cost of the heat exchanger.

Heat exchanger performance is quantified by means of a parameter known as the effectiveness, e. Effectiveness compares the rate of heat transfer, Q_{real}, occurring between the hot and cold fluids within an actual device, and the maximum possible rate of heat transfer, Q_{max}, that would take place in a counterflow heat exchanger, with infinite heat transfer surface area, operating at the same mass flow rates and the same inlet states of the two fluids. In a counterflow heat exchanger, the two fluids flow in opposite directions, i.e., the colder fluid enters at the outlet of the warmer fluid flow path, and exits at its inlet.

The requirement that heat transfer can occur spontaneously only from a warmer body to a cooler body, imposed by the second law of thermodynamics, establishes the value of Q_{max}. If it is assumed that there are no heat losses to the environment, then it can then be shown that Q_{max} is attained when the outlet temperature of the cooler fluid reaches the inlet temperature of the warmer fluid, for $m_cCp_c < m_hCp_h$, or, alternatively, when the outlet temperature of the warmer fluid reaches the inlet temperature of the cooler fluid, for $m_hCp_h < m_cCp_c$. Here, the subscripts c and h indicate conditions in the cooler and warmer fluid, respectively, and Cp is the constant pressure specific heat. It follows that

$$e = Q_{real}/Q_{max} \approx [m_hCp_h\,(T_{hin} - T_{hout})]/[x\,(T_{hin} - T_{cin})]$$

or

$$[m_cCp_c\,(T_{cin} - T_{cout})]/[x\,(T_{hin} - T_{cin})]\,,$$

where the subscripts $_{in}$ and $_{out}$ respectively denote conditions at the inlets and outlets and x is the smaller of m_hCp_h and m_cCp_c. The approximate expressions for e given above assume that changes in fluid enthalpy can be expressed as the product of a constant specific heat and a corresponding change in temperature.

The principal advantage of utilizing an effectiveness in design calculations is that both the rate of heat transfer and the states of the two fluids exiting the heat exchanger may be determined explicitly, given a value of e and the inlet states of the two fluid streams. Other methods, such as the LMTD (logarithmic mean temperature difference) analysis, require an implicit, iterative process to converge on the outlet states and Q_{real}.

Low energy conversion efficiencies of OTEC cycles require that thermal energy extracted from warm, surface seawater and rejected to cold, deep seawater, exceed by nearly an order of magnitude the amount of work generated. As a consequence, huge flow rates of seawater will be required by commercial-scale OTEC plants.

It must be pointed out that the expression for the efficiency of the Carnot 2T heat engine given earlier does not consider the energy required to transport seawater to and from the power generating equipment. This pumping process is taken to be external to the 2T heat engine, and the energy consumed must be subtracted from the work output. As a consequence, the overall efficiency, both theoretical and real, of the OTEC cycle will be reduced further. Since the magnitude of this reduction scales directly with the amount of energy consumed in the pumping process, it is necessary for us to quantify this parasitic loss.

Rough estimates of the seawater pumping power may be obtained employing the modified Bernoulli equation. Although relying on a high degree of empiricism, this expression, like those presented earlier for the component efficiencies, is simple to use and provides adequate results for many engineering analyses. If the subscripts 1 and 2 denote, respectively, the upstream and downstream ends of a section of circular pipe between which any number of valves, joints, or other passive flow operators may be installed, then, assuming zero heat transfer between the pipe and its surroundings,

$$(P_1 - P_2) + [r(V_1^2 - V_2^2)/2] + [rg(z_1 - z_2)] = \Sigma\, [(f\, L\, rV^2)/(2\, D)] + \Sigma(KrV^2/2).$$

In this equation, r is the liquid density, assumed constant, V is the average velocity at the relevant location, and z is the elevation. The two summations on the right hand side account for friction losses occurring in the boundary layer adjacent to the pipe wall and fluid dynamic losses in valves, joints, etc. The friction factor, f, which depends on, among other things, pipe Reynolds number and wall roughness, is given in Moody diagrams. D is the inner diameter of the pipe, L is the length of pipe over which a set of values of f, V, and D are fixed, and K is an experimentally-determined pressure drop factor.

The modified Bernoulli equation describes the pressure drop, $(P_1 - P_2)$, arising from a flow of liquid through a pipe. To sustain this flow, a pump may be required downstream of 2 to bring the liquid pressure up to ambient (or some other desired value). Given the liquid flow rate, P_2, and the desired pump exit pressure (i.e., the pressure ratio across the pump), an analysis utilizing an appropriate value of h_{pump} will determine the pumping power requirement. It should be observed that if the modified Bernoulli equation indicates that, for a given liquid flow rate and P_1, P_2 is equal to the local ambient at 2, then no external energy input is required.

If P_3 is the liquid pressure at the exit of a pump placed immediately downstream of location 2, and if fluid kinetic and potential energy changes across this pump can be neglected, then a good approximation of W_s/m, the power consumed per unit mass flow of liquid through an ideal pump, is

$$W_s/m \; ' \; (P_3 - P_2)/r \, .$$

Hence,

$$W_{real}/m \; ' \; (P_3 - P_2)/(r \, h_{pump}) \, .$$

From the Bernoulli equation,

$$\begin{aligned}(P_3 - P_2) = (P_3 - P_1) + [r(V_2^2 - V_1^2)/2] + [rg\,(z_2 - z_1)] \\ + \Sigma\,[(f\,L\,rV^2)/(2\,D)] + \Sigma\,(K\,rV^2/2)\, .\end{aligned}$$

It follows that

$$\begin{aligned}W_{real}/m \; ' \; (1/h_{pump})\,\{[(P_3 - P_1)/r] + [(V_2^2 - V_1^2)/2] + [g\,(z_2 - z_1)] \\ + \Sigma\,[(f\,L\,V^2)/(2\,D)] + \Sigma\,(K\,V^2/2)\}\, .\end{aligned}$$

A popular misconception about OTEC is that, due to the resisting gravitational force, an enormous amount of power must be consumed to bring seawater up to the surface from depths approaching 1000 m. The above equation for W_{real}/m shows that this is not true. Assuming that the density of seawater remains constant, pressure varies linearly with depth according to

$$P(z) = P_{atm} - r\,g\,z\, ,$$

where P_{atm} is the atmospheric pressure and z increases moving upward toward the ocean surface (where $z = 0$). If P_3 is taken to equal P_{atm}, then the terms $[(P_3 - P_1)/r]$ and $[g\,(z_2 - z_1)]$ cancel. Moreover, if the pipe diameters at 1 and 2 are the same, then $V_2 = V_1$. Under these circumstances, pumping power only is required to overcome frictional effects in the long, submerged pipeline.

1.5 OTEC Economics and Externalities

There are at least two distinct markets for OTEC: (1) industrialized nations and islands; and (2) smaller or less industrialized islands. Developing islands with modest needs for electrical power and fresh water are ideally suited for open-cycle plants, which can be sized to produce from 1 to 10 MW electricity, and from 450 thousand to 8 million gallons of fresh water per day (1,700 to 30,000 m^3/day). Hybrid cycle plants can be used in either market for producing electricity and water. For example, a 40 MW hybrid cycle plant could also produce as much as 16 million gallons of water per day (60,600 m^3/day).

Scenarios under which OTEC might be competitive with conventional technologies, in the production of electricity and water, have been assessed (Vega and Trenka, 1989). The capital cost for OTEC plants, expressed in 1989 \$/kW, was established assuming modest engineering development. The relative capital cost of producing electricity (\$/kWh) with OTEC, offset by the desalinated water production, was then equated to the fuel cost of electricity produced with conventional techniques to determine the scenarios (i.e., fuel cost and cost of fresh water production) under which OTEC could be competitive. No attempt was made at speculating about the future cost of fuel. It was simply stated that if a situation is represented by one of the scenarios, OTEC would be competitive. Four scenarios are listed Table 3.

Table 3. OTEC market penetration scenarios

Nominal Net Power (NWe)	Type	Scenario Reqts	Scenario Availability
1	Land-Based OC-OTEC with 2nd-Stage additional Water Production	• \$45/barrel of diesel • 1 6M^3 water	South Pacific Island Nations by Year 1995
10	Land-Based (as above)	• \$25/barrel of fuel oil • \$0 85/m^3 water - or - • \$30/barrel with • \$0.8/m^3 water	American Island Territories and other Pacific Islands by Year 2000
40	Land-Based Hybrid (ammonia power cycle w/Flash Evaporator downstream)	• \$44/barrel of fuel oil • \$0 4/m^3 water - or - • \$22/barrel • \$0 8/m^3 water	Hawaii, if fuel or water cost doubles by Year 2000
40	• Closed-Cycle Land-based • Closed-Cycle Plantship	• \$36/barrel • \$23/barrel	 By Year 2005

• OC-OTEC limited by turbine technology to 2.5 MW modules or 10 MW plant (with four modules)
• OC-OTEC or Hybrid (water production downstream of closed-cycle with flash evaporator)

One scenario corresponds to small island nations, where the cost of diesel-generated electricity and fresh water is such that a small, 1 MW, land-based open-cycle OTEC plant, with water production, would be cost effective today.

A second scenario corresponds to conditions that are plausible in the near future in, for example, territories like Guam, American Samoa, and Northern Mariana Islands, where land-based open-cycle OTEC plants rated at 10 MW could be cost effective if credit is given for the fresh water produced. A third scenario corresponds to land-based hybrid OTEC plants for the industrialized nations market producing electricity through an ammonia cycle and fresh water through a flash (vacuum) evaporator. This scenario would be cost effective with a doubling of the cost of oil fuel or doubling of water costs, and for plants rated at 40 MW or larger. The fourth scenario is for floating OTEC electrical plants, rated at 40 MW or larger, and housing a factory or transmitting electricity to shore via a submarine power cable. These plants could be deployed throughout the tropical regions of the ocean basins and could encompass a large market.

Since environmental protection has been recognized as a global issue, another important point to consider is the preservation of the environment in the area of the selected site, inasmuch as preservation of the environment anywhere is bound to have positive effects elsewhere. OTEC offers one of the most benign power production technology, since no hazardous substances need to be handled, and no noxious by-products are generated. OTEC merely requires the pumping and discharge of various seawater masses, which should be accomplished with minimal adverse environmental impact. This argument should be very attractive, for pristine island ecosystems, as well as for already polluted and overburdened environments.

One major difficulty with OTEC is not of a technological order: the capital-intensivity, and the first plants constructed, will require substantial capital investment. Given the prevailing low cost of crude oil, and of fossil fuels in general, the development of OTEC technologies is likely to be promoted by government agencies rather than by private industry. The motivation of governments in subsidizing OTEC may vary greatly, from foreign aid to domestic concerns.

For the former case, ideal recipient countries are likely to be independent developing nations. If these countries' economic standing is too low, however, the installation of an OTEC plant rather than direct aid in the form of money and goods may be perceived as inadequate help. In addition, political instability could jeopardize the good will of helping nations to invest. For the latter case, potential sites belong to, or fall within the jurisdiction of, developed countries: examples include Hawaii, Taiwan, Tahiti, American Samoa, the Northern Marianas, and Guam.

A study performed in 1981 for the U. S. Department of State identified ninety-eight nations and territories with access to the OTEC resource within their 200 nautical mile exclusive economic zone (EEZ). A representative list is reproduced in Table 4. For the majority of these locations, the OTEC resource is applicable only to floating plants (arbitrarily assuming that the length of the cold water pipe for a land-based plant should not exceed 3,000 meters). A significant market potential for OTEC (577,000 MW of new baseload electric power facilities) was postulated. Unfortunately, now as then, there is no commercial OTEC plant with an operational record available. This remains the major impediment to widespread OTEC development.

Table 4. Nations and territories with access to the OTEC thermal resource

GEOGRAPHICAL AREA	MAINLAND		ISLAND	
AMERICAS	Mexico	Guyana	Cuba	Guadeloupe (FR)
	Brazil	Suriname	Haiti	Martinique (FR)
	Colombia	French Guiana (FR)	Dominican Rep.	Barbados
	Costa Rica	Nicaragua	Jamaica	Dominica
	Guatemala	El Salvador	Virgin Is. (US)	St. Lucia
	Honduras	Belize	Grenada	St. Kitts (UK)
	Panama	United States	St. Vincent	Barbuda (UK)
	Venezuela		Grand Cayman (UK)	Montserrat (UK)
			Antigua (UK)	The Grenadines (UK)
			Puerto Rico (US)	Curacao (NETH)
			Trinidad & Tobago	Aruba (NETH)
			Bahamas	
AFRICA	Nigeria	Gabon	Sao Tome & Principe	
	Ghana	Benin	Ascension (UK)	
	Ivory Coast	Zaire	Comoros	
	Kenya	Angola	Aldabra (UK)	
	Tanzania	Cameroon	Madagascar	
	Congo	Mozambique		
	Guinea	Eq. Guinea		
	Sierra Leone	Togo		
	Liberia	Somalia		
INDIAN/PACIFIC OCEAN	India	Australia	Indonesia	American Samoa (US)
	Burma	Japan	Philippines	Trust Territories (US)
	China	Thailand	Sri Lanka	Northern Marianas
	Vietnam	Hong Kong (UK)	Papua New Guinea	Guam (US)
	Bangladesh	Brunei	Taiwan	Kiribati
	Malaysia		Fiji	French Polynesia (FR)
			Nauru	New Caledonia (FR)
			Seychelles	Diego Garcia
			Maldives	Tuvalu
			New Hebrides (UK/FR)	Wake Is. (US)
			Samoa	Solomon Is.
			Tonga	Mauritius
			Cook Is.	Okinawa (JAPAN)
				Wallis & Futuna Is. (FR)
				Hawaii

The capital costs required to build OTEC plants have been estimated assuming cost reductions via modest engineering development after the design, construction and operation of demonstration plants. The cost figures expressed in 1989 dollars are summarized on Tables 5 and 6 for plants rated at 1, 10 and 40 MW with the indicated desalinated water production. It is assumed that 1 MW land-based plants could be deployed some time after 1995. Their commercialization must be preceded by the installation of a demonstration plant of 1 MW and 3,500 cubic meters/day of desalinated water. These plants would be designed utilizing the state-of-the-art bottom-mounted cold water pipe technology (1.6 meter diameter, high-density polyethylene pipe).

The design of 10 MW land-based open-cycle plant would be scaled from the 1 MW demonstration plant with a new design for bottom-mounted cold water pipes. The commercialization of 40 MW land-based plants must be preceded by the design and operation of a 5 MW closed-cycle demonstration plant. These plants also require the development of larger diameter (> 1.6 meters) cold water pipes.

To consider the moored or slowly drifting OTEC plantship, a capital cost of 4,600 S/kW-net is estimated for an electrical production of 380 x 106 kWh (slightly higher than for the land-based plants because of lower pumping power requirements). The cost differential between the moored and the drifting vessels are insignificant at this level

Table 5. Levelized (amortized) cost of electricity with desalinated water credit at 0.4 S/m^3

PLANT CF=80%	Production Electricity kWh	Production Water m^3/day	Capital Cost $/kW-net	Fixed Charge	O&M % of Capital	Levelized Electricity Cost with Water Production Credit 4/kWh
1 MW OC OTEC Land Based	8.10E+06	1,700	18,200	10%	1.7%	0.27
1 MW OC OTEC Land Based 2nd Stage	7.30E+06	3,560	23,000	10%	1.7%	0.31
10 MW OC OTEC Land Based	7.00E+07	15,000	10,700	10%	1.5%	0.14
10 MW OC OTEC Land Based 2nd Stage	6.30E+07	30,000	14,700	10%	1.5%	0.17
40 MW CC OTEC Land Based	3.36E+08	0	6,000	10%	1.5%	0.10
40 MW CC OTEC Land Based 2nd Stage	2.80E+08	60,600	9,400	10%	1.5%	0.12
40 MW CC OTEC Floater	3.80E+08	0	4,600	10%	1.5%	0.08

Table 6. Levelized (amortized) cost of electricity with desalinated water credit at 0.8 $/m³

PLANT CF=80%	Production Electricity kWh	Production Water m^3/day	Capital Cost $/kW-net	Fixed Charge	O&M % of Capital	Levelized Electricity Cost with Water Production Credit ¢/kWh
1 MW OC OTEC Land Based	8.10E+06	1,700	18,200	10%	1.7%	0.24
1 MW OC OTEC Land Based 2nd Stage	7.30E+06	3,560	23,000	10%	1.7%	0.24
10 MW OC OTEC Land Based	7.00E+07	15,000	10,700	10%	1.5%	0.11
10 MW OC OTEC Land Based 2nd Stage	6.30E+07	30,000	14,700	10%	1.5%	0.10
40 MW CC OTEC Land Based	3.36E+08	0	6,000	10%	1.5%	0.10
40 MW CC OTEC Land Based 2nd Stage	2.80E+08	60,600	9,400	10%	1.5%	0.09
40 MW CC OTEC Floater	3.80E+08	0	4,600	10%	1.5%	0.08

of discussion because the savings in mooring system and power cable are offset by the propulsion and positioning requirements, as well as by the product transport, for the factory ship. These plants would be designed utilizing the methodology already available for cold water pipes suspended from a vessel.

The following formula, proposed by the Electric Power Research Institute, is used to calculate the production cost of electricity p levelized over the assumed life for the OTEC plant (nominal value: 30 years):

$$p\ (\$/\text{kWh}) = (FC.CC + OM.G.CR)\ /\ (NP.CF.8760)$$

FC : annual fixed charge, taken as 0.10
CC : plant overall investment capital cost, in $
OM : operation and maintenance yearly $ expenditures
G : present worth factor, in years, estimated value 20
CR : capital recovery factor, taken as 0.09
NP : net power production, in kW
CF : production capacity factor, chosen as 0.80
8760 : number of hours in one year (CF.8760 = 7,000)

The first term simply represents the payment for a fixed interest loan valued at CC, $, over a prescribed term expressed in hourly payments, where, the loan is for a plant rated at a power of NP, kW. The second term models the levelized cost of operating and maintaining the plant over the term. Usually the OM costs are not levelized.

For closed-cycle plants, p is estimated with no credit taken for the sale of the fresh water by-product. For open or hybrid cycle plants, fresh water credit is obtained by multiplying the unit price by the yearly production and subtracting the result from the numerator of the expression given above. For the sake of completeness, costs estimated in this fashion are given on Tables 5 and 6 for unit prices of water at 0.4 $\$/m^3$ and 0.8 $\$/m^3$ respectively with the OM costs expressed as a percentage of capital and unlevelized. These estimates illustrate the importance of the water revenue for the small plants (1 to 10 MW), especially with the unit price of water at twice the present rate.

In addition to the fresh water produced by the open-cycle, OTEC offers potential for mariculture co-products and can provide the chiller fluid for air-conditioning systems. The cold seawater contains large quantities of the nutrients required to sustain marine life. Organisms already grown in this environment in Hawaii include algae, seaweeds, shell fish and fin fish. Although a number of species have been identified as technically feasible, further work is required to identify cost effective culture methods for the available markets. OTEC mariculture is in its formative years and still somewhat risky for commercial development.

The relatively small portion of the cold seawater can also be used as the chiller fluid for air-conditioning systems. A system based on this concept is presently utilized at NELH for one of the buildings. However, this application is seen to be of some significance for small open-cycle OTEC plants, but is insignificant for larger plants. With the exception of the relatively small use of the cold seawater as AC chiller fluid, OTEC should be considered for its potential production of electricity and desalinated water.

Like any offshore or shoreline project, commercial OTEC facilities will affect the marine environment. 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, and maintenance routines 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 deep depths. However, OTEC systems can be designed and located to minimize their potential effects on the environment and even enhance the surrounding ocean, as shown by Mini-OTEC, when augmented fish catches were reported near the site off the Kona Coast of the Big Island of Hawaii.

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, 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 (SERI, 1989). 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.

OTEC plants discharge large quantities of ocean water and could potentially affect 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. However, a key point to consider is that, the intelligent management of this discharge could stimulate living marine resources.

An environmental impact of a more serious nature could occur if ammonia, Freon, or some other environmentally-hazardous working fluid was 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 plant could release enough ammonia to destroy marine organisms over an area as large as four square kilometers (SERI, 1989).

2. Tidal Power

Coastal geography and bathymetry are important factors for the extraction of energy from the tides. Tides involve the rise and fall of the ocean, combining the gravitational pulls of the sun and moon with the rotation of the earth. The influence they have on the ocean can be amplified by natural configurations of coastline and sea bottom to provide differences between high and low tide of up to 16 meters (50 feet). Under such conditions, tidal energy conversion can occur utilizing relatively conventional hydroelectric turbines and related structures.

The primary factors influencing the height and timing of the tides include:

- the rotation of the earth on its axis (24 hours/rotation),
- the moon's orbit around the earth (29.53 days),
- the earth's orbit around the sun (365.24 days),
- the position of the moon with respect to the equator, and
- the distance from the moon to the earth (apogee/perigee).

Tidal energy extraction requires a strong ocean effect and a natural resonant inshore configuration to make it work economically. Just as hydroelectric power depends on natural differences in elevation of the terrain, tidal power depends on the natural configuration of inshore coastal features. There are relatively few coastal areas where conditions combine to produce the degree of resonance required. Natural and celestial circumstances appear to limit tidal energy development to within latitudes of 50 to 60 degrees (Warnock, 1987).

For a tidal cycle of 6.2 hours, the potential energy (E) can be estimated to be:

$$E(\mathrm{kW}) = 226\ A(H^2)$$

where A is the surface area of the enclosed tidal basin in square kilometers and H is the tidal range in meters. The total annual power (P) is the following:

$$P(\mathrm{GWh}) = 2.0\ A(H^2)$$

This relationship is derived by multiplying the energy (E) by 365 days/year and 24 hours/day (ECOR, 1989).

Conditions necessary for efficient and economic tidal energy conversion systems include:

- a tidal range of at least three meters (ten feet),
- an enclosed basin,
- solid submarine ground, and
- short transmission distance or means of energy storage.

Countries with operational tidal energy systems are France, the former Soviet Union, Canada, and China (Table 7). The La Rance tidal power station on the west coast of France, with an installed capacity of 240 MW, is the world's largest ocean energy conversion plant. Construction began in 1961 and was completed by 1968. The powerhouse is 332 meters long, housing twenty-four 10 MW bulb-turbine units. The plant has been operational since 1968 with 95 percent availability.

Table 7. Major Tidal Power Projects

Country	Location	Tidal Range (m)	Output (MW)	Initial Operation
China	Shashan	5.1	0.040	1959
France	La Rance	8.5	240	1966
USSR	Kislaya Guba	3.9	0.400	1968
China	Jingang Creek	5.1	0.165	1970
China	Jiangxia Creek	5.1	3.2	1980
Canada	Annapolis Royal	7.1	19.1	1984
Canada	Cumberland	10.5	1428	Planned
Canada	Minas Basin	12.4	5338	Planned
United States	Cobscook Bay	5.4	300	Planned
United States	Cook Inlet	9.4	1440	Proposed
United Kingdom	Severn Estuary	11.0	7200	Planned
United Kingdom	Mersey Barrage	6.5	620	Proposed
India	Rann of Kutch	5.3	600	Proposed
S. Korea	Garolim Bay	4.8	480	Proposed
USSR	Mezen Bay	6.5	15,000	Proposed
USSR	Sea of Okhotsk	7.7	10,000	Proposed
Argentina	Puerto Gallegos	12.0	400	Proposed
Australia	Walcott Inlet	6.0	1300	Proposed

In 1968, the former Soviet Union put into operation a 400 kW pilot plant in Kislaya Bay. Called the Kislogubskaya pilot plant, it pioneered floating construction techniques. In 1985, the former Soviet Union announced plans to build a tidal plant on the White Sea coast with a generating capacity of 15,000 MW. The Mezenskaya plant is still in the preliminary stages of planning.

The Canadian tidal power project is the 20 MW plant at Annapolis Royal, Nova Scotia. This plant was built by the Nova Scotia Power Corporation. Located on the Annapolis River near its outlet at the Bay of Fundy, the plant contains a single "Straflo" hydropower turbine and has been operational since 1984. Presently, Canada is investigating the potential of such turbines for larger scale installations in the Bay of Fundy, and for low-head river developments.

In the People's Republic of China, tidal energy was first reported in 1959 with the installation of a 40 kW plant located in Shashan. A 165 kW tidal plant was later built in 1970 in the Shandong Province on the Jingang Creek. In May 1980, China's first two-way tidal plant, rated at 500 kW, began operating on the Jiangxia Creek near the Zhousan Islands. This plant was later expanded to 3.2 MW in 1986.

In the United Kingdom, a Salford transverse oscillator project with an installed capacity of 270 kW is under construction by Crouch and Hogg Consulting Engineers and Salford Civil Engineering, Ltd. This prototype barrage will be used to supply electricity to a hospital located in the Outer Hebrides, Scotland. Additionally, work is being conducted by the Severn Tidal Power group on a preliminary design for the Severn tidal power project, an ebbtide generating plant to be located on the Severn River estuary (Saris, 1989).

The United States has designed one tidal power plant for installation in the state of Maine. Called the Half Moon Cove Tidal Project, its installed capacity is planned to be 12 MW using two 6 MW units. Additional tidal power projects are planned for the Bay of Fundy in Canada, Cook Inlet in Alaska, Garolim Bay along the west coast of Korea, and Rann of Kutch in northwestern part of India (Warnock and Clark, 1992). The Korea Ocean Resource Development Institute (KORDI) recently announced the initiation of a major tidal power development project.

Tidal power generation is possible only when the available head (difference between basin and sea level) exceeds a certain threshold. This results in generation during less than 50% of the time. At the beginning and end of the power phase, when head is low, generation is less than capacity while during higher head, constant output is achieved by regulating turbine flow. Because the moon's position relative to the earth varies over a period of 24 hours and 50 minutes, tidal phase shifts every day. Hence generation occurs at different times on different days and will not always coincide with peak electrical demand.

The United Kingdom has conducted a design study of a tidal plant at a site (Langstone Harbor, Hampshire) that had a 3 meter mean annual tidal range generating 24.3 MW on the ebb tide cycle. Construction cost was estimated at $2,813/kW and electricity produced at $0.16/kWh in 1986 dollars. In constant 1990 dollars, this equates to about $3,511/kW and electricity cost at $0.19/kWh.

Both positive and negative environmental effects can be expected from the development of tidal power plants. While potential effects would be very site-specific, they may be grouped into several categories based on the physical changes brought about by construction and operation of the plant. These include the physical presence of the dam, changes in water level, changes in flow patterns and current velocities, and changes in sediment patterns (Carmichael et al., 1986).

During construction, dredging operations (including disposal), blasting, and placement of rock fill or concrete structures will impact benthic habitats, increase turbidity (thus affecting organisms within the water column), and may restrict navigation. These impacts would be short-term and local, and would vary depending on whether float-in or cofferdam construction were employed. Once constructed, the physical presence of the dam represents permanent changes which could affect recreational use of the water and impoundment, navigation, and fish passage and habitat. Locks can be used to assist navigation and, in some cases, navigation within the basin could be improved by higher average water levels.

The opportunity to build a road across the dam would be a major positive benefit, especially at large sites. The generally smaller tidal ranges, as discussed below, would offer increased opportunity for recreational boating. Because of the large volumes of water involved, entrainment of fish in plant turbines could be a problem. For example, shad migrate through the Bay of Fundy and concern over their entrainment has been cited in regards to potential Bay of Fundy tidal power projects (Carmichael et al., 1986).

3. Wave Energy Conversion

Ocean wave energy conversion technologies utilize the kinetic energy of ocean waves to produce power. Wave energy is a potential environmentally benign and renewable energy resource. The general approaches to converting wave energy into electricity can be broadly categorized by means of deployment and means of energy extraction and conversion. Means of deployment include floating deep-water technologies and shallow-water, fixed-bottom technologies. Means of energy extraction and conversion include mechanical cams, gears, and levers; hydraulic pumps; pneumatic turbines; oscillating water columns; and funnelling devices. At present, five wave energy systems generate a total of 535 kW of power, and two more commercial systems will be operating by 1992 (Table 8).

The two components of energy within waves are potential energy and kinetic energy. Potential energy is associated with the form or elevation of the wave. Kinetic energy is associated with the movement or velocity of the water particles beneath the wave. The total energy of a wave is the sum of its potential and kinetic energy. For regular (sinusoidal) waves,

$$E = (mgH^2)/8$$

where E is the total energy per unit of water surface area, m is the mass density of ocean water ($\approx 1030\ kg/m^3$), g is the gravitational acceleration ($\approx 9.81\ m/s^2$), and H is the wave height from trough to crest.

Table 8. Major Wave Energy Developments

LOCATION	TECHNOLOGY	RATING	STATUS
TOFTESTALEN, NORWAY	MULTIRESONANT OWC	500 kW	OPERATED 1985-1989
TOFTESTALEN, NORWAY	TAPERED CHANNEL	350 kW	OPERATING SINCE 1986
TASMANIA, AUSTRALIA	TAPERED CHANNEL	1.5 MW	BEGIN CONSTRUCTION-1991
JAVA, INDONESIA	TAPERED CHANNEL	1.5 MW	BEGIN CONSTRUCTION-1991
ISLE OF ISLAY, SCOTLAND	SHORE-BASED OWC	75 kW	OPERATING SINCE 1990
SAKATA PORT, JAPAN	BREAKWATER OWC	60 kW	OPERATING SINCE 1989
KUJUKURI, JAPAN	SHORE-BASED OWC	30 kW	OPERATING SINCE 1988
MASHIKE HARBOR, JAPAN	B.W. PIVOTING FLAP	20 kW	OPERATING SINCE 1983
KAIMEI (SHIP), JAPAN	BARGE-MOUNTED OWC	125 kW	OPERATED 1978-80, 85-86
GOTHENBURG, SWEDEN	HEAVING BUOY	30 kW	OPERATED 1983-1984
COPENHAGEN, DENMARK	HEAVING BUOY	45 kW	TESTED-SPRING, 1990
PUERTO RICO, USA	HEAVING BUOY	NONE	DESALINATION PROJECT

The transfer of wave energy is known as wave power or energy flux. Small amplitude waves in deep water (depth>wavelength/2) will, according to linear theory, have a power per unit of wave crest width of:

$$P = E(c/2) = mg^2H^2T / 32P \; ' \; 0.98\, H^2T \quad (\mathrm{kW/m})$$

where, c is wave speed or phase velocity and
m = water density in kg/m^3
g = gravitational acceleration in m/s^2
H = wave height in meters
T = wave period in seconds

For H=2 meters and T=10 seconds in deep water, wave power is approximately 40 kW per meter of crest width (Carmichael and Falnes, 1992).

The corresponding relation for random seas (irregular waves) is:

$$P = 0.5\, H^2{}_S\, T_Z \quad (\mathrm{kW/m}),$$

where H_S = significant wave height; the average wave height of the largest 1/3 of the observed waves, and T_Z = average time interval between successive crossings of the mean high water level as it moves upward. This equation must be used to avoid overestimating wave energy potential, since waves are generally irregular in the ocean (ECOR, 1989).

The approaches to converting wave energy into electricity can be broadly categorized by means of deployment and means of energy capture and conversion. The six general approaches to wave energy conversion are:

1. surge devices - utilizing the forward horizontal force of the waves,
2. oscillating water columns - conversion of wave induced fluctuations,
3. heaving floats - utilizing the vertical motion of relatively small buoys,
4. heaving and pitching floats - absorbs energy from heaving and pitching,
5. pitching devices - utilizing the pitching moment of rotary pumps,
6. heave and surge devices - utilizing heave and surge to pump water.

Table 9 contains information on some of the better known wave energy devices including the system name, the country in which it was developed, and the type of conversion employed.

Table 9. Wave Energy Conversion Systems

SYSTEM NAME	COUNTRY	TYPE OF CONVERSION
TAPERED CHANNEL	NORWAY	SURGE DEVICE
MULTI-RESONANT OWC	NORWAY	OSCILLATING WATER COLUMN
BACKWARD BENT DUCT BUOY	JAPAN	OSCILLATING WATER COLUMN
PENDULUM TYPE DEVICE	JAPAN	SURGE DEVICE
NEPTUNE SYSTEM	AUSTRALIA	OSCILLATING WATER COLUMN
KN SYSTEM	DENMARK	HEAVING FLOAT
HOSE PUMP	SWEDEN	HEAVING FLOAT
WAVE ENERGY MODULE	CANADA	HEAVING/PITCHING FLOAT
CONTOURING RAFT	USA	HEAVING/PITCHING FLOAT
NODDING DUCK	UK	PITCHING DEVICE
SEA CLAM	UK	SURGE DEVICE
BRISTOL CYLINDER	UK	HEAVE/SURGE DEVICE

Wave energy research and development funding by various governments is estimated to be (White, 1991):

United Kingdom - $20 million

Norway - $12 million

Japan - $10 million

Sweden - $5 million

Denmark - $3 million

The United Kingdom wave energy program was initiated in 1974. Recent projects include wave-powered desalination and pumping, investigation of the use of a Wells turbine in naturally-occurring rock gullies, construction of a 150 kW prototype wave power plant on the Scottish Island of Islay, production of wave-powered turbine generators for navigational buoys in Northern Ireland, and development and model testing of a small-scale wave energy converter at Loch Ness by Coventry Polytechnic. Systems developed and evaluated from 1974 to 1985, include a wide range of configurations of wave energy converters designed for relatively large outputs. Three of the more well-known are the Nodding (Salter) Duck, Sea Clam, and Bristol Cylinder.

Norway has conducted an extensive wave power program since 1975. In the 1980s, these efforts culminated in the installation by Kvaerner Brug of a 500 kilowatt wave power system, called the multiresonant oscillating water column (MOWC), at Toftestallen on the west coast of Norway. This system operated from November 1985 until the plant was swept off its foundation and destroyed during a severe, 100-year storm near the end of 1988. Preliminary agreements with the island countries of the Azores and Mauritius to build additional power stations. (Kerwin, 1990).

Another pilot system, the 350 kilowatt tapered channel wave power plant (Tapchan), was installed at Toftestallen by Norwave and has been operational since 1986. Contracts have been signed with the governments of Indonesia and Tasmania by Norwave. Typically, a tapered channel is carved out of a rocky coastal area, using shaped charges, if necessary. The taper can handle a wide spectrum of wave lengths efficiently. As a wave passes through the tapered channel, its wave height is gradually increased as the channel narrows. The wave then spills over into a reservoir where it is stored and subsequently passes through a low-head Kaplan water turbine to generate electricity. The construction costs range from about $2,000/kW in Java to $3,550/kW in Tasmania and the systems are expected to produce power at rates of about 5 to 10 cents per kilowatt hour (Vadus, 1991).

The Japanese government has had a very active wave energy research and development program for many years. Applications under investigation range from wave power generators for lighthouses and light buoys to wave pump systems, ship propulsion, and energy for road heating, heat recovery systems, and fish farming. Several technologies have been examined by both government and industry under the Japanese wave energy program. These include floating terminator-type wave devices, fixed coastal-type wave power extractors, and applications of oscillating water column turbines. The most well known project, supported by the International Energy Agency, was the Kaimei, a 500-ton barge-like platform containing about ten oscillating water columns. Wave action produces oscillations of the water column that produce pneumatic power which is converted to electrical power via air turbo-generators.

The Port and Harbor Research Institute, Ministry of Transport is currently developing a wave energy absorption type caisson breakwater called a wave power extracting caisson. The performance of the breakwater is improved, in terms of stability against waves and reduction of reflected waves, by providing air chambers which serve as energy converters. The air chamber and machine room containing the turbine-generator system are located in the upper part of the caisson. The front wall of the air chamber is inclined at an angle of 45 degrees and is one-half meter thick. Large external pressure forces are expected to act on this wall from incoming waves, as well as large air pressure forces internally. During field work at Sakata Port in the Sea of Japan, the conversion ratio from wave to air power was 0.5, turbine efficiency was 0.39, and the generator efficiency was 0.92 (Miyazaki, 1991).

In Sweden, the use of an oscillating buoy as a wave energy converter has been extensively studied. Field tests of a 30 kW prototype hose-pump device were completed from 1983-84. Negotiations are currently underway for a 1 MW pilot plant to be installed off the Atlantic coast of Spain. India has announced plans to aggressively develop wave power over a six-year time period beginning in 1990. The Indian wave energy program includes plans to build a 5 MW offshore plant near Madras. Presently, a 150 kW demonstration plant using a Wells turbine-generator is under construction at a fishing harbor near the port of Trivandrum.

Wave energy activity in the United States has included research and development on a pneumatic wave energy conversion system, prototype testing of a parallel disk wave energy module, tandem-flap system, and contouring raft device, and research into hose-pump type wave-powered desalination in Puerto Rico (Saris, 1989).

The impact on the environment of wave energy conversion is strongly dependent on the scale of the activity. When a modest project is proposed, the impacts are likely to be small; however, there will be community resistance should recreational sites be compromised. The conversion of wave energy to electricity may be expected to influence the coastal wave and current climate, the populations of fish and marine mammals, the navigation of ships, and the visual environment. A large wave power conversion system would modify the local wave climate. A reduction in the wave energy arriving at the shores can change the density and balance of species of organisms around the coast, and may modify the deposition of sand on the beaches (Carmichael et al., 1986).

The wave energy conversion devices may influence the population of fish and marine mammals in the near vicinity. Bottom feeding fish and shellfish, such as lobster and crab, are likely to be unaffected. Fish and marine mammals that spend much of their life near the surface require more consideration. Salmon, members of the herring family, and even sea lions have been mentioned as species that will have to be evaluated when impacts of large-scale wave energy conversion systems are considered.

Wave energy converters placed in or near shipping lanes would present a hazard to shipping because their relatively low profile would make them less visible to sight and radar. The devices would have to be properly marked, and navigation channels would have to be provided through large arrays of the converters. Mooring failures resulting in drifting of the floating devices would provide an additional hazard to navigation and shoreline structures (Carmichael et al., 1986).

The visual effects of wave energy will depend on the site selected, size of the floating platforms, the length of the array, distance offshore, and method of cable transmission. Shore-based systems such as Tapchan may be blended into the coast and require a relatively low-profile reservoir ashore to provide the necessary head of water. Depending on the power, the profile of an array can be barge-like and could require a long line of such structures. The visual effect will depend on how far offshore and the impact is difficult to generalize because each configuration and installation plan will differ from one location to another. The visual effect of a large array of wave energy converters could be minimal because of the low profile of the devices in the array, and because they would normally be placed some distance offshore. The main adverse visual effect is likely to be power distribution lines from the shore to the grid. Other concerns involve the impact on coastal recreational sites, offshore oil and gas exploration, and military usage of the coastal zone. The economics of wave energy conversion is also a major concern including construction costs, capacity factors, operation and maintenance costs, reliability, survivability, and the intermittent nature and seasonality of the resource (White,1991).

4. Other Sources of Ocean Energy

4.1 Ocean Currents

The kinetic energy of river currents has been used from medieval times to produce power using simple water turbines. There are many old prints that show mechanical power produced from mills at bridges to pump river water to the adjacent communities. The proposed application of current turbines in the oceans is a comparatively recent development, and has been prompted by the observations of mariners and oceanographers of the swiftly-flowing current in some regions of the world. The Gulf Stream, or more specifically, the Florida Current, is of particular interest because of the high current velocity and its proximity to large centers of population on the Florida coast.

The performance of an ocean current turbine is similar to the performance of a wind turbine. The ocean or wind turbine transforms a proportion of the kinetic energy of the flow into mechanical power. A small ocean turbine was demonstrated in 1985 in the Florida Current. The unit was suspended from a research vessel at a depth of 50 meters and developed approximately 2 kW. The project was privately funded, and a proposal made to design and test 100 kW and 1 to 2 MW units of a similar design (Carmichael et al., 1986). More recently, a feasibility study was conducted concerning the utilization of currents in the Strait of Messina in Italy. The study included a basic design of the system, as well as a preliminary environment impact assessment (Beru and Garbuglia, 1993).

In addition, a 20 kW prototype turbine, designed by UEK Corporation, is under research and development, for which testing is planned in New York City's tidal East River. Since 1979, Canadian researchers at Nova Energy Ltd. have been developing large Darrieus-type vertical axis turbines for hydropower applications and are presently completing testing of a 5 kW prototype. Australian current energy conversion units designed by Tyson Turbines Ltd. are small to medium size modular devices capable of producing an energy output of more than 670 kW depending on depth and stream velocity. These units are commercially available for a variety of applications and have been demonstrated in many countries including Australia, the Philippines, Mexico, the United States, and Canada (Saris, 1989).

From simple momentum analyses, it can be shown that the maximum power (P), that can be extracted from an ideal, non-ducted (open) turbine occurs when the turbine reduces the velocity of the stream to 1/3 of its initial value (Carmichael et al., 1986), hence

$$P\ (\mathrm{kW}) = Cp\ (1/2\ mV^3S)$$

where,

Cp = power coefficient (= 16/27 for an ideal turbine)

V = fluid velocity, m/sec

S = turbine disk area, m^2

m = fluid density, kg/m^3

The Gulf Stream carries 30 million cubic meters of water per second, more than 50 times the total flow in all of the world's freshwater rivers; the surface velocity sometimes exceeds 2.5 meters per second. The extractable power is about 2,000 watts per square meter and would, therefore, require extremely large, slow-rotating blade turbines operating like windmills. The total energy of this Florida current is estimated to be about 25,000 MW.

In 1979, the Aeroenvironment Company conducted a conceptual design study (Coriolis Project) based on installing very large diameter turbines in the Gulf Stream. Energy calculations indicated that an array of 242 large turbines, each about 170 meters in diameter, moored in the Gulf Stream in an array occupying an area of 30 kilometers cross-stream and 60 kilometers downstream would produce about 10,000 MW. This is the energy equivalent of about 130 million barrels of oil per year.

Cost estimates indicated that each unit could be built and installed at about $1,200/kW in 1978 dollars. Including capital, operating, maintenance, and fuel costs, power is delivered at about $0.040/kWh in 1978 dollars. These figures assumed a plant factor of 57%, which is computed in a way similar to that used for wind turbines, by considering the seasonal variation in the current, plus a two-week annual maintenance shutdown. The Coriolis system is an environmentally benign, cost-efficient method of extracting energy from a renewable source (Lissaman, 1979).

The environmental effect of an array of Coriolis ocean turbines on the Florida Gulf Stream current has been investigated for several models. The results showed that for an annual average extraction of 10,000 megawatts, the reduction in speed of the Gulf Stream is estimated at about 1.2 percent, much less than its natural fluctuation. Further calculations indicated that any heating effects resulting from turbulence in the wake of the turbines would be very small (Lissaman, 1979). A one meter diameter turbine with compliant blades and rim-driven system was constructed and demonstrated in a water flume. No further research and development was conducted. However, more research is needed to provide greater confidence in technical and economic feasibility in constructing, installing, and mooring very large turbines of the size proposed. Current energy systems do not appear to be ready for commercial application at this time.

4.2 Salinity Gradients

A large unused source of energy exists at the interface between freshwater and saltwater, and the extent of energy depends on the salinity gradient (Table 10). In extracting this salinity gradient energy, the heart of most systems is a semi-permeable membrane that allows water, but not dissolved solids, to pass through the membrane. With freshwater on one side and saltwater on the other side of the membrane, the force of the freshwater through the membrane creates an osmotic pressure difference. As freshwater permeates through the membrane, a head of water is developed with respect to the saltwater, and a turbine can be used to extract energy from the water flow.

The energy difference that exists between fresh water and salt water depends on the salinity gradient and is represented thermodynamically as the difference in the free energy at the temperature of the two flows of water. The power that could be produced from any salinity gradient device increases with salinity difference and would be

Table 10. Potential Power from Salinity Gradients (Monney, 1977)

Source	Country	Flow Rate (10^4 m/sec)	Pressure (atm)	Power (10^6 kW)
Run-Off	Global	110.0	24.0	2,600.0
Run-Off	USA	5.3	24.0	130.0
Amazon River	Brazil	20.0	24.0	470.0
La Plata-Parana River	Argentina	8.0	24.0	190.0
Congo River	Congo/Angola	5.7	24.0	130.0
Yangtze River	China	2.2	24.0	52.0
Ganges River	Bangladesh	2.0	24.0	47.0
Mississippi River	USA	1.8	24.0	42.0
Salt Lake	USA	0.0125	300.0	1.8
Dead Sea	Israel/Jordan	0.0038	300.0	1.8
Wastewater to Ocean	USA	0.05	22.5	1.1

particularly effective when the salt water is a dense brine. Power may be generated from the free energy difference in various ways: in a hydraulic system using the difference in osmotic pressure between freshwater and seawater; as electrical energy in a reverse electrodialysis cell; or in a vapor turbine utilizing the difference in vapor pressure between fresh water and sea water. An additional method of using the free energy in a salinity gradient has been devised utilizing the extension and contraction of special fibers induced by changes in salinity (Carmichael et al., 1986).

The development of candidate systems for the production of power from salinity gradients has not progressed far enough to provide an accurate economic assessment of system types and configurations. However, general considerations can be presented which point to one concept which may be promising if the salinity gradient is very large, such as where the Jordan River flows into the Dead Sea. An Analysis and preliminary experiments for a 100 MW plant at the mouth of the Jordan River indicate that power could be produced at a cost of $0.072/kWh in 1976 dollars (Monney, 1977).

Although this cost is more than double the cost of electricity from a coal-fired power plant, dramatic improvements may be possible for the salinity gradient power plant with improvements in semipermeable membranes. A brine such as that which exists at the Dead Sea or Great Salt Lake can be used to produce a greater salinity gradient. Another difficulty is that geographical areas with naturally occurring bodies of high salinity brine are usually deficient in the fresh water needed to provide the salinity gradient. However, it may be possible to use sea water or other brackish water as the low salinity permeate. It may even be feasible to create a renewable energy resource by using sea water in evaporating ponds in a coastal area to produce the high salinity brines which would be mixed with the low salinity sea water permeate.

In an evaluation of the subsystems and components which would comprise a salinity gradient power plant, it becomes apparent that the semi-permeable membrane is the major technical problem. In all other respects, the plant would draw upon well established technical capabilities which have little potential for marked improvements. The membrane, however, has a very significant potential for improvement in terms of cost and performance and, at the same time, is the major controlling factor in determining the power output of a plant operating with a specified salinity gradient. The major problems with respect to semi-permeable membrane development are flux, fouling, salt rejection, life expectancy, and cost. The production of power from the salinity gradient between fresh water and sea water will not be economically feasible unless the membrane flux can be improved by an order of magnitude and the requirement for pre-treatment of the water can be virtually eliminated.

5. Associated Products from Ocean Energy Systems

5.1 Fuel Production

The alternative fuels and energy-enhanced products considered in this section fall into two broad categories: (1) resource-based, in which marine biomass is converted into a fuel, a biologically derived product is produced, or a mineral resource is extracted from the sea; and (2) energy-derived, in which the electricity generated from an ocean energy resource (e.g. thermal gradients, tides, waves, currents, salinity gradients) is a major component in the manufacturing of products such as hydrogen, ammonia, or alcohol.

The biological resource-based component is itself dependent upon mineral resources, although nutrients within the biogeochemical global ecosystem are not always categorized as a mineral resource. The deep waters of all the world's oceans contain the accumulated nutrients of thousands of centuries of growth and decay from terrestrial and surface marine waters. The resurfacing of this nutrient resource in areas of natural upwelling adjacent to coasts acccunts for the majority of marine fisheries and bioresources.

It is reported that in these naturally upwelled sites, 0.1% of the ocean surface produces 44% of the fish catch (Roels, 1980). Maximizing marine productivity requires the judicious use of this resource. More conventional mineral resources within the basins of the world's oceans also represent a vast and largely untapped source of new materials. These materials could be of strategic, international importance because of their potential impact on balancing the unequal distribution of mineral resources which exists in the terrestrial realm.

Farming of aquatic biomass, mainly macroalgae, is one approach of taking advantage of nutrient-rich, pathogen-free, deep ocean waters, and of ocean energy conversion systems. Today, marine biomass is being used for the production of colloidal compounds such as alginic acid, carrageenan, and agar; for human consumption; as an animal feed supplement; and as fertilizers and soil conditioners. The increasing demand for fuels and other high-valued products, coupled with the diminishing ability of land-based resources to meet the growing demand for such products, has stimulated a search for more efficient ways to tap the ocean's biological resources.

Yield studies pertaining to near-shore (along the coast or in tidal flats) and deep-ocean (in rope curtains or in floating lenses) production of macroalgae have been encouraging. Ryther (1979) investigated the growth rates of *Gracilaria sp.* and *Macrocystis pyrifera* and found that the potential yields of these macroalgae species were comparable to or better than most terrestrial crops. North (1987) investigated the potential for open ocean farming of *Macrocystis* and concluded that, while many problems existed relating to large scale farming in the open ocean, technological advancements were capable of overcoming those problems. He also determined that artificial upwelling of deep ocean water was an appropriate fertilizing technique to provide nutrients to enhance algal growth rates. Experiments on land have been reported (Dugan et al., 1987).

A number of thermochemical and biochemical processes could be employed to convert the energy contained in biomass into a more usable form; however, very few technologies are well suited for feedstocks with high (>80%) moisture content, as is typically the case with marine plants. Processes include: (1) anaerobic digestion, to produce a medium energy content biogas (containing 50%-60% methane with the remainder mostly carbon dioxide) which could be burned directly to generate electrical power, refined into pipeline quality methane, or converted into methanol using existing technology; (2) fermentation, to produce alcohols or other high-valued organic compounds such as acetone; and (3) an exciting study (Manarungson et al., 1990) which investigated the gasification of high-moisture content marine algae to produce hydrogen using supercritical water.

In comparison with terrestrial biomass, little is known of the microbiology and biochemistry of anaerobic digestion of marine macroalgae. However, the limited research that has been performed on bioconversion of marine biomass into methane has produced encouraging results—rapid and nearly complete conversion, and process stability, seem to be inherent in biochemical conversion of marine biomass. For example, Chynoweth, Fannin, and Srivastava (1987) studied the potential for biological gasification of marine algae (primarily *Macrocystis*) and concluded that marine algae were excellent feedstocks for the production of methane. They found that anaerobic digestion of *Macrocystis pyrifera* yielded more than 80% of the theoretically attainable methane, the highest yield ever reported for any non-waste biomass.

Of the many marine plants available for bioconversion into methane, two subgroups of the brown kelp (Phaeophyta) phyla, *Macrocystis pyrifera* (best in temperate seas or for cultivation in cool, upwelled water) and *Sargassum* (best in tropical seas), hold the most promise. A schematic for a hypothetical marine biomass-to-methane bioconversion system is shown in Figure 9. In this fuel production scenario, 335 tons (dry basis) of marine biomass per day would produce 19,900 tons (one million GJ) of methane annually.

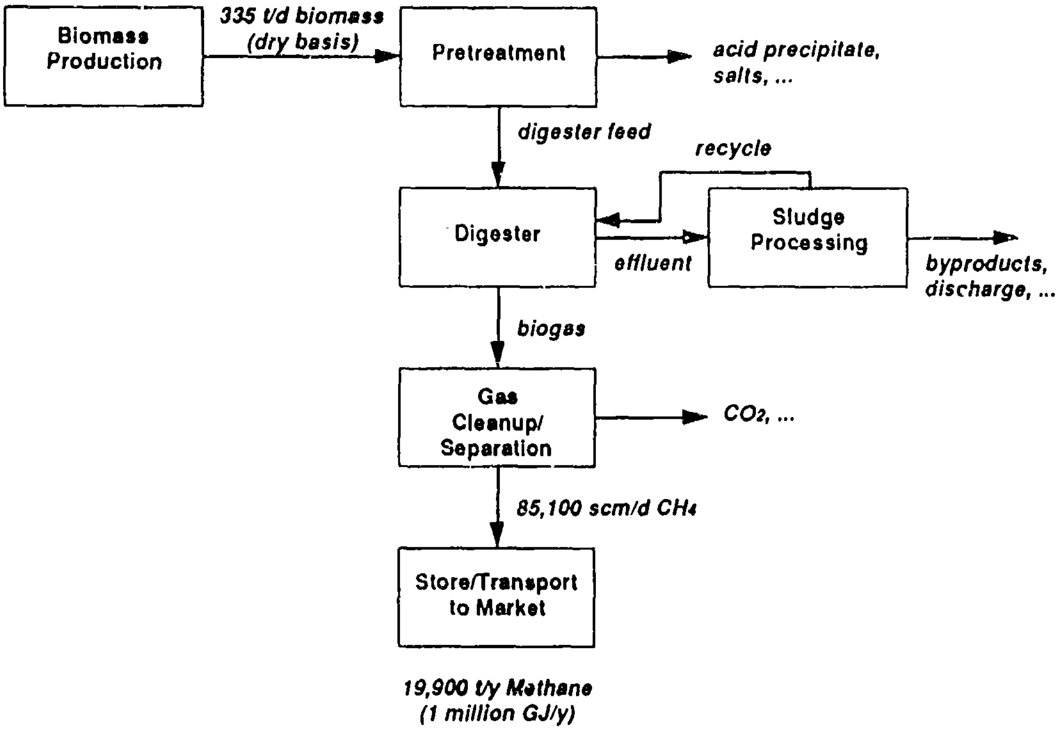

Figure 9. Biomass-based methane production facility producing 19,900 tons of methane (with net heating value of 1 million GJ) annually. (Based on data from Murata and Keller, 1977)

A number of potential by-products could complement the production of methane from macroalgae. For example, more than twenty potential products which could be co-produced with methane from kelp have been identified in the literature (Bird, 1987). A cost analysis on energy from marine biomass suggested that its economic feasibility lies in limiting energy costs by exploiting potentially available ocean energy systems and in enhancing methane production with revenues from by-products. Calculations indicated that co-production of energy and chemical products could more than double gross sales receipts over producing only methane.

Conversion of biomass into methane is not as energy intensive as electricity-based options. Therefore, in most of the biomass-to-methane systems proposed to date, the bioconversion plant was assumed to be located on land and not integrated with an ocean energy electrical generating facility. However, marine biomass production could be greatly enhanced by using the nutrient-rich cold water upwelled by an OTEC facility, which suggests an advantage in integrating biomass production with OTEC power generation. In addition, the lower "land" cost and relative ease of harvesting and transporting the feedstock to a nearby floating platform would provide economic advantages. While studies (Longwell, 1989) showed that methanol from terrestrial biomass was not economically attractive, methanol from marine biomass could have a more favorable future.

As an alternative to the production of methane, marine biomass could be converted into alcohol fuels via fermentation. Minimal research has been performed in this area, and cost projections are preliminary. The process of converting marine biomass into ethanol would resemble that employed for grains. Conversion of marine biomass would probably require more energy input due to the higher moisture content in the feedstock and may require an initial hydrolysis step to break down the complex hydrocolloids into fermentable oligosaccharides (Bird, 1987). Overall conversion would be strongly influenced by the proportion of soluble carbohydrates to total carbohydrates, which, in marine biomass, can vary from 20% to 70%. Genetic engineering developments may improve this option in the future.

Offshore oil and natural gas represent developed energy resources, but methane hydrate deposits and deep oil and gas reserves are two examples of fossil-fuel sources of oceanic origin that are worthy of mention. Methane hydrate, a clatherate of water molecules surrounding methane gas, exists in significant concentrations throughout the ocean floor. It has not been tapped as a source of fuel thus far because of the lack of technology associated with the mining of the crystals and their conversion into usable methane.

The potential benefits that can be accrued by combining deep ocean mining with ocean energy recovery have sparked interest in such an integrated approach. The best sites for many ocean energy systems such as OTEC are in proximity to sites for deep ocean mining (Grote, 1981). Processing in the region of mining could greatly reduce transportation and waste disposal costs associated with the pyrometallurgical process used in refining manganese nodules into cobalt, copper, and nickel.

The water needed for cooling in ore processing could be taken directly from the adjacent sea water, or in a more integrated approach, from the cold water pumping stream of an OTEC plant. Utilizing the cold deep ocean waters in this way could accomplish two goals: (1) cooling in the metallurgical process and (2) heating of nutrient-rich waters for subsequent use in open ocean mariculture, which is important because, otherwise, the cold deep ocean water might sink below the euphotic zone before the nutrients could be consumed by marine biomass.

The ocean is a storehouse of minerals, and sodium chloride continues to be extracted through an evaporative process. Bromine and magnesium until recently were produced from sea water on an industrial scale. The Japanese have conducted considerable research on extracting uranium from sea water. However, the projected payback was not sufficient for commercial applications.

The large volume of OTEC fluids has sparked recent interest on the recovery of gold and other trace metals. The value of gold passing through a one megawatt OTEC power plant exceeds $50 million each year. Concepts such as the synthesis of special molecules (24-pyrimidium Crown 6) have been funded by PICHTR, and genetic engineering micro-organisms to adsorb specific elements have also been suggested.

Feedstock conversion processes that require substantial input of power could capitalize on energy from the ocean if the cost of the energy were relatively low. Examples of feed materials that potentially might be used in power-intensive processes to produce transportable fuels and energy-enhanced products include sea water, marine biomass, seabed ores, coal, and municipal wastes. Sea water would be converted into hydrogen and oxygen via ocean-energy powered electrolysis; these, in turn, could be used in the processing of other products such as ammonia. Marine biomass would be converted into liquid fuels such as methanol and other energy-enhanced products (e.g., fertilizers) and chemicals. Seabed ores mined near the power generating facility could be processed on site, utilizing the energy produced for the smelting and refining processes in converting the raw ores into commercial grade metals.

Such feed materials have the advantage of potentially being extracted in proximity to, or produced in conjunction with, an ocean-based power system; therefore, high shipping costs would not be incurred in transporting the material from distant locations to the plant site. Coal and municipal wastes and other terrestrial feedstocks have also been considered for use with ocean energy conversion systems in the production of methane or methanol. Such feedstocks would have to be transported from land to power production facilities in the ocean where they would then be converted into other products. Therefore, it is advantageous to integrate marine biomass plantations with ocean platform facilities.

Process diagrams for three of the fuel production options mentioned above, hydrogen, ammonia, and methanol (Avery et al., 1985), are shown in Figures 10, 11, and 12. The size of the systems relate to a common production unit (one million GJ) for the net heating value of fuel produced. The abbreviations MW_e and MW_t denote electrical and thermal energy transfers, respectively. Each of these fuel options employs a common base process, electrolysis of desalinated water, using electricity generated by an ocean energy conversion plantship, to produce gaseous hydrogen and oxygen. Additional steps are added to the base process to produce the desired product.

Hydrogen is regarded by many to be the best long-term alternative to fossil fuels, as it is renewable when produced from renewable resources and environmentally benign. Avery (1988) investigated the production of hydrogen via water electrolysis in 50-400 MW OTEC plantships. The analysis indicated that power could be generated on plantships of that size range at costs low enough to permit fuels and other products (ammonia, fertilizers, etc.) to be manufactured on board and delivered to land-based users at prices approaching those for products from conventional methods of production that utilize fossil fuel or nuclear power.

In the OTEC-hydrogen plantship concept (Figure 10), 64 megawatts of net power production from an ocean energy conversion facility could produce 8270 tons (one million GJ) of hydrogen per year. The low density and low boiling point of the hydrogen produced would demand special handling and storage measures at additional cost. Hydrogen, once liquefied, would be shipped to market in tankers designed for low density cryogenic liquids or embedded into metal hydrides or another convenient carrier, and then regenerated as needed.

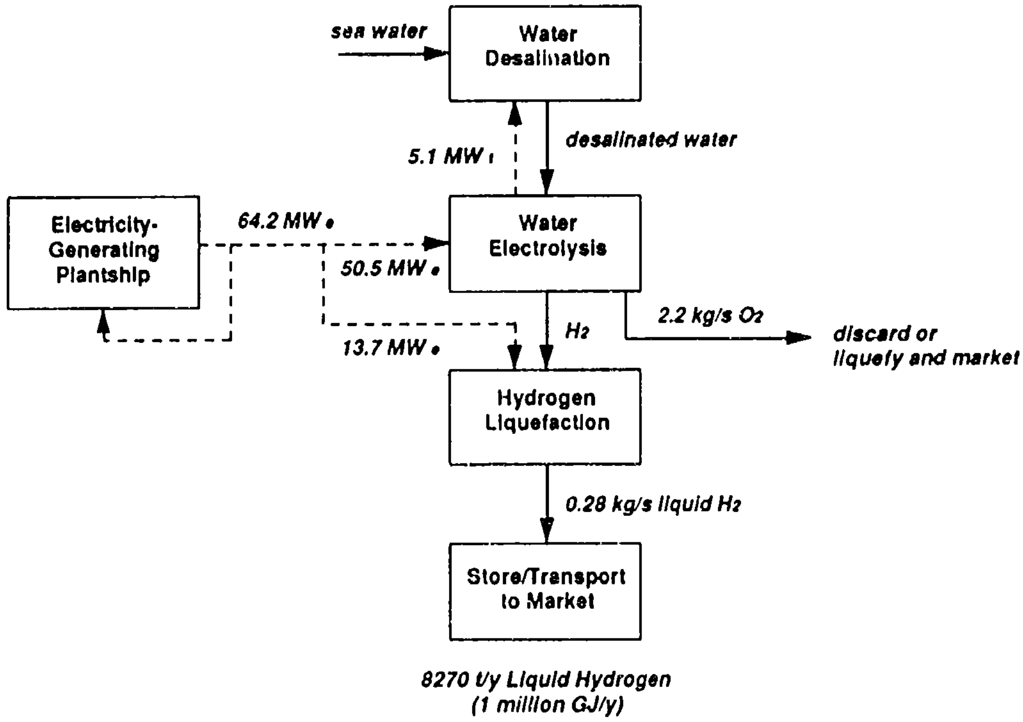

Figure 10. Electricity-based hydrogen production facility producing 8270 tons of liquid hydrogen (with net heating value of 1 million GJ) annually. (Based on data from Avery, Richards, and Dugger 1985)

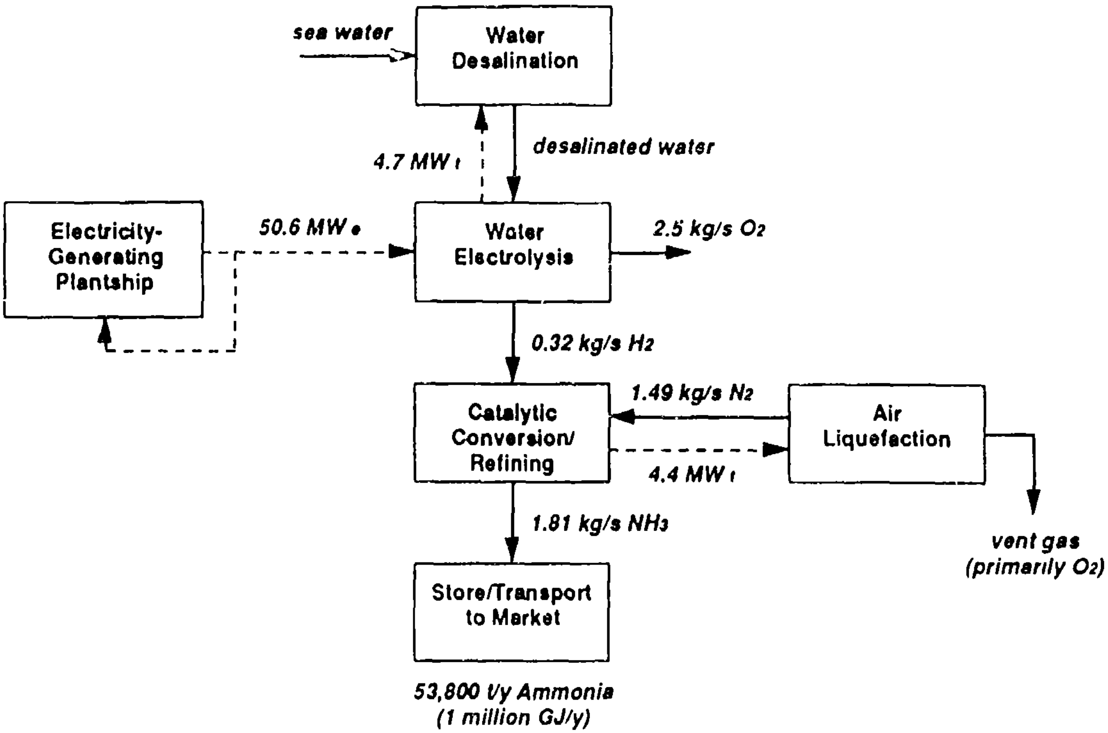

Figure 11. Electricity-based ammonia production facility producing 53,800 tons of ammonia (with net heating value of 1 million GJ) annually. (Based on data from Avery, Richards, and Dugger 1985)

Ammonia exists in liquid form at moderate pressures and temperatures, is much easier to handle than hydrogen, and contains more hydrogen per unit volume than metal hydrides or than liquid hydrogen itself. In addition, ammonia is a good fuel in its own right and is a base for the production of fertilizers and industrial chemicals. For subsequent transportation and energy utilization, it may be more economical to convert the hydrogen produced in a plantship into ammonia. A survey (Richards and Henderson, 1981) of previous work on the use of ammonia as a fuel noted that much of the distribution infrastructure and markets for ammonia already existed. They concluded that ammonia produced by ocean energy plantships could become an economical fuel in the near future.

In the ammonia production scenario, electricity from an ocean energy conversion facility would be used to produce nitrogen via air liquefaction. The nitrogen would then be combined with the hydrogen generated as described earlier and catalytically converted into ammonia. Figure 11 shows a 51 megawatt (net) electrical generating facility capable of producing 53,800 tons (one million GJ) of ammonia annually.

Methanol has been acclaimed as the best near-term alternative to conventional ground transportation fuels, gasoline and diesel, from the standpoints of cost, performance, and ease of handling and distribution. The potentially large demand for methanol and its likelihood of being accepted into the market, make methanol a strong candidate for production in ocean-based manufacturing plants. In the ocean-based methanol production scenario, a carbonaceous feedstock (coal, biomass, biogas, or the like) would be partially oxidized with oxygen produced by electrolysis as described above into carbon monoxide and other gases. The carbon monoxide would then be combined with hydrogen from the electrolysis plant and catalytically converted into methanol.

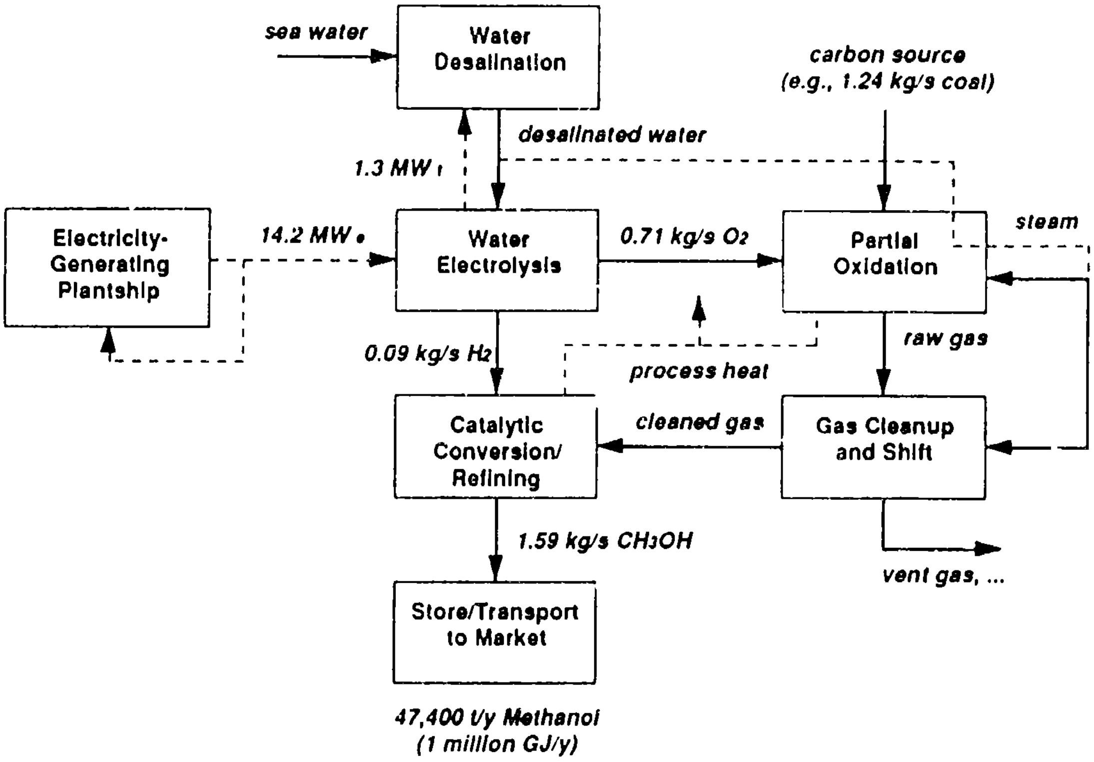

Figure 12. Electricity-based methanol production facility producing 47,400 tons of methanol (with net heating value of 1 million GJ) annually. (Based on data from Avery, Richards, and Dugger 1985)

In the coal-to-methanol scenario (Figure 12), 14 megawatts (net) of electricity from the plantship combined with 107 tons of coal per day (1.24 kg/s) would produce 47,400 tons (one million GJ) of methanol annually, thus yielding 1.3 tons of methanol per ton of coal By comparison, land-based coal-to-methanol plants (which would obtain most of the required hydrogen by reacting coal with water and oxygen and which would employ air liquefaction to produce the necessary oxygen) would probably be capable of yielding only 0.5 to 0.7 tons of methanol per ton of coal (Avery and Richards, 1982).

Marine biomass could be converted into methanol in much the same manner as coal. The yield of methanol from gasified biomass could be more than doubled by adding sufficient hydrogen to the intermediate gas stream to obtain the stoichiometric hydrogen:carbon monoxide ratio for methanol synthesis (Takahashi et al., 1990);

comparable methanol yield increases could be achieved with marine biomass by adding hydrogen produced by an ocean-based electrolysis plant to the product gas. If desired, the methanol produced by the plantship could be converted into gasoline (via the Mobil process). Alternatively, the methanol production step could be bypassed through the use of special catalysts (Parmon, 1989).

Energy from ocean resources can also be used synergistically in the manufacturing of various non-fuel products. For example, several studies have suggested that ocean-derived electrical power be used for alumina-to-aluminum reduction. Combining the reduction process with ocean energy conversion is attractive because (1) the reduction process, which is energy intensive (approximately 15.4 kWh/kg aluminum is required for the electrolysis cells and ancillary demand), could fully take advantage of ocean-derived electricity; and (2) ocean-based alumina reduction plants could facilitate reduction and minimize shipping costs by being located along alumina shipping routes near Hawaii, Puerto Rico, South American coasts, and Australia (Dugger et al., 1981).

5.2 Deep Ocean Water

Deep ocean water contains considerably more nutrients than the waters near the surface (Table 11). As the majority of the nitrogen and phosphorus is derived from the decay of previous biological production from the upper layers of the world's oceans, deep ocean water represents an ideal source of nutrients for photosynthesis and mariculture (Takahashi et al., 1993).

Table 11. Comparison of Surface and Deep (600 meters) Seawater

Parameter	**Surface Water**	**Deep Ocean Water**
Temperature (°C)	26	8.9
Nitrogen (NO_3 plus NO_2)	0.2	39.0
Nitrogen (NH_4)	0.4	0.2
Phosphorous (PO_4)	0.2	3.0

The key to the biological utilization of deep ocean water is availability of light. Natural biological processes readily utilize the nutrients via algal photosynthesis if sufficient light is available for the process. Nutrients accumulate at depth because there is insufficient light below the thermal discontinuity for significant photosynthetic activity. When deep water reaches the surface through natural means a zone of high primary and secondary productivity is generated. These zones of upwelling, nearly all associated with continental shelf areas, produce much of the world's total fisheries catch.

Before examining the difficulties in utilizing deep ocean water, let us first calculate the potential of "artificial upwelling" areas for producing fish protein or biomass from macroalgae. First, how much water are we considering? For the purpose of discussion, we will examine the nutrient potential associated with a 40 megawatt net power generating plant. By most standards this is a modest generating capacity, serving between 40,000 and 80,000 persons or a moderate industrial base.

Such a plant would produce a combined (cold plus warm) seawater flow of 800 m^3/sec or 69 million m^3/day. Using the NELH water quality data as a starting point, we can calculate that 69 million m^3/day of water, i.e., nutrient poor surface water combined with enriched deep ocean water on a 1:1 basis, delivers approximately 8000 tons of nitrogen to the euphotic zone annually. If we assume that kelp is 1% nitrogen on a dry-weight basis (Neushul, 1990) and fish is 10% nitrogen on a dry-weight basis (Kennish, 1989), we can estimate production quantities that could be generated by such a nutrient stream. Assuming a conversion efficiency of 10% for primary producers and 1% for secondary consumers we can roughly estimate that deep ocean water could generate some 80,000 tons (dry weight) of kelp per year, or 800 tons of fish.

While the promise of deep ocean water may be great, much preliminary work on the nutrient biogeochemistry and the physics associated with deep ocean water discharges is still required. A workshop in March of 1990 in Kona, Hawaii, sponsored by the National Science Foundation and Science and Technology Agency of Japan explored the following topics:

artificial upwelling devices,
ocean water discharges and hydrodynamic mixing,
mariculture facilities systems development,
growth kinetics of marine organisms in deep ocean water,
species selection for mariculture and open ocean ranching,
the environmental impact of deep ocean water, and
nutrient biogeochemistry (major and trace nutrient dynamics).

Also, a much better understanding of the nutrient dynamics of areas of natural upwelling. Once we understand the ecological efficiencies associated with nutrient dynamics of natural upwelling areas, we can outline realistic goals for artificial upwelling systems.

Two multi-year experiments have now been completed in Japan. An (at-sea) experiment on artificial upwelling was conducted in Toyama Bay, in western Japan (Kajikawa, 1991). For this experiment cold water was taken from a depth of 230 meters and mixed with warm surface water in a ratio of 1:2. The combined discharge was approximately 1 m^3/sec and the discharge was sprayed on the surface during the summers of 1989 and 1990. While this experiment represented an important step forward and information concerning water discharge behaviors was obtained, the volume of water was generally too small to sustain any nutrient-rich plume under real ocean conditions. Either greater discharges need to be tested, or a more protected site used so that the discharges are not so heavily impacted by local currents and eddies.

Japan's second multi-year effort involves a land-based facility near Cape Muroto in southern Japan. The Kochi Artificial Upwelling Laboratory draws deep ocean water from a depth of 320 meters. Surface water is also available for mixing with deep water and for experimentation. Controlled experiments in growth kinetics and species selection have been successfully completed here. In many instances, complementary work has been conducted at Hawaii's own deep ocean water complex at NELH. As with the Toyama Bay experiment, this facility is also limited by the quantity of water that can be pumped, maximum rates of approximately 0.005 m^3/sec. The next phase of work for this laboratory complex will feature the temporary enrichment of the near-shore marine environment. In order to accomplish this next phase, a pipeline system of much greater capacity will have to be installed.

Various estimates have been made of the total amount of material available for food from the ocean. Biological evidence is strong that the limit for conventional seafood products is about 100 to 120 million metric tons. However, it has been stated that a harvest of 400 to 700 million metric tons from the ocean might be possible using the following methods (Idyll, 1978):

harvest plant and animal plankton,
harvest seaweed and other large aquatic plants,
develop technology to farm the ocean (mariculture),
transplantation/stocking of natural marine populations, and
make more efficient use of the present catch.

We will focus on mariculture and its future development potential, especially in the open ocean environment.

Mariculture is a term used to designate aquaculture within the marine environment. Since the marine environment includes bays and estuaries, as well as the world's oceans, open ocean mariculture is used to distinguish culturing activity in unprotected marine waters, regardless of its distance to the nearest coastline. Open ocean mariculture is a relatively new concept. Although much of the fundamental technology that it appears to require is already well advanced, new applications will be needed. Therefore, the initial establishment of open ocean mariculture facilities is expected to be expensive, in terms of technology development cost versus market return, unless major components of the necessary technology can be acquired through means other than outright purchase.

Some advantages from locating a mariculture facility in the open ocean include (P2M, 1991):

An unlimited supply of clean, pollution-free water available at different temperatures (by pumping water from different depths).

Avoidance of coastal-zone conflicts including:

- no required land use,
- less visual impact of facility on coastal inhabitants, and
- virtually no effect of facility waste effluents on the coastline.

Increased survival, growth rates, stocking densities, and product quality due to:

- superior water quality,
- increased water circulation,
- minimal fluctuation of temperature and salinity,
- less exposure to bacterial and parasitic pathogens, and
- minimal effect from external pollution sources.

Facility mobility, allowing for the:

- avoidance of hurricanes, typhoons, and cyclones,
- avoidance of oil spills,
- avoidance of plankton blooms, and
- option to change location (seasonally or otherwise).

The transfer of materials and equipment can occur at sea without the use of conventional harbor and port facilities.

In addition, an open ocean mariculture facility can be developed in conjunction with artificial upwelling of nutrient-rich water, electrical power production, deep seabed mining and other ocean resources (Takahashi and Yuen, 1991). Figure 13 illustrates such a system utilizing a floating platform for a base of operations.

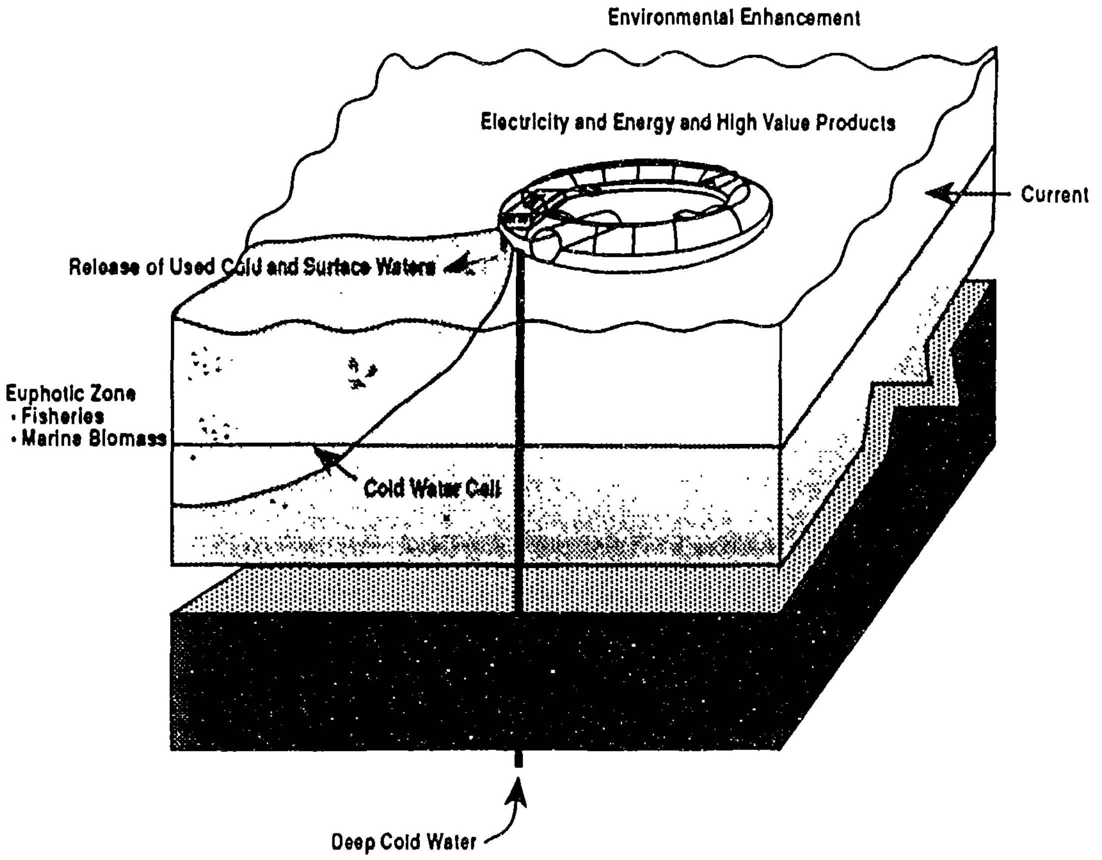

Figure 13. Floating Platform Concept

The open ocean environment has enormous potential for mariculture; however, surface waters are practically nutrient deserts. Thus, the most promising concept for mariculture in the open ocean is artificial upwelling. Since than 40% of world's fisheries catch comes from 0.1% of the ocean's area, where natural upwelling occurs, artificially upwelled fisheries hold particular hope for creating a new maritime industry.

Although the benefits mentioned above are important to consider, the open ocean remains a more uncertain legal and political environment to operate in than the coastal zone. Moving away from the overlapping jurisdictions of local, state and federal governments is an appealing prospect; however, constraints of a more international nature will be encountered. While an enormous amount of time and money is required to satisfy the numerous regulations concerning the use of near-shore waters, at least they are discernable. The requirements to be satisfied in offshore waters are yet to be determined, as well as the extent to which a mariculture facility operating offshore could be legally protected.

Since operations must be conducted within a combination of legal, political, and technological constraints, the implications are that open ocean mariculture will be economically feasible only when some combination of two conditions exists (Hanson, 1974). The first condition is a high market value for the resulting products. The second is a level of scientific and technological advancement that allows the maximum utilization of natural energy fluxes and other natural and human-generated phenomena in the offshore environment. While the cost of producing food from agriculture and fisheries are expected to continue to rise exponentially due to decreasing land, fossil-fuels, and natural fish stocks, mariculture costs should continue to decline with technological improvements and become increasingly competitive with time.

A critical prerequisite to the design of an open ocean mariculture facility is the selection of species best suited for culture. Both the bioeconomics and the economics of production must be considered. The first of these is directly concerned with the biology of the species, the technological level of culture presently developed and environmental compatibility. The second component depends on production logistics including capital costs, operational costs, labor and marketing.

The biological suitability of a species for mariculture or any other farming practice depends upon a combination of several associated factors. The most important of these appear to be the following (Nash, 1974):

gregarious nature,
high fecundity,
short reproductive life cycle,
high survival rate,
natural trophic level,
rapid growth rate (high biomass rate of production),
high protein content of tissues, and
inherent behavior (environmental compatibility).

Production economics are primarily influenced by local environmental benefits and costs due to the geographical, topographical, chemical, biological and social properties of a proposed site. The following production factors should be considered before design can begin (Nash, 1974):

- availability of juveniles,
- logistics and cost of food supply,
- labor costs,
- containment costs,
- processing costs, and
- potential market demand and value.

The last factor listed may be the most critical since until cultured species can establish their own level of quality and command a premium price, production costs will have to compete with those of commercial fisheries, which markets chilled or frozen products at dockside prices or processes them on fishing vessels.

Some candidate species for open ocean mariculture are evaluated in Table 12 based on potential market demand and value. Species with the best market potential (not necessarily food markets) include: oysters, lobster, brine shrimp, salmon, and turtle. Species with high market potential include: clams, scallops, abalone, shrimp, dolphinfish (mahi), and yellowfin tuna (ahi). Table 12 refers to groups of species rather than individuals, and is based on data for the best individual species in the group that have been cultured or studied. It is not intended to be used in place of a current, more detailed marketing study, but is an illustration of the type of result which could be expected from such a study (Bregman et al., 1992).

The final selection of species for open ocean mariculture should also consider additional regional and location-specific factors. These include oceanographic parameters such as salinity, temperature, current movements and strengths, sea states and other environmental factors, as well as labor resources, local market proximity and conditions, governmental support, financial resource availability, and other socio-economic aspects.

Containment systems for fish involve either physical enclosures or aggregation devices (passive containment). Submersible cages appear to be the only type of physical containment having any potential for open ocean applications. The advantages of submersible cages over conventional cages include (Svealv, 1991):

- positioning at optimum water depth to maximize fish growth and survival rates and minimize marine biofouling,
- avoidance of storms, surface debris, and other potentially damaging environmental forces, and
- removal from water layers with superchilled water or algae blooms.

Table 12. Market Potential for Species Selection

SPECIES	PRICE (a)	U.S. (b)	FOREIGN (c)	TOTAL
OYSTERS	5	5	5	15
CLAMS	4	5	5	14
SCALLOPS	4	5	5	14
ABALONE	4	5	5	14
MUSSELS	2	1	5	8
LOBSTER	5	5	5	15
BRINE SHRIMP	5	5	5	15
SHRIMP	4	5	5	14
CRAB	1	2	3	6
KRILL	1	1	3	5
SALMON	5	5	5	15
DOLPHINFISH	4	5	5	14
YELLOWFIN TUNA	5	4	5	14
POMPANO	4	5	4	13
FLATFISH	3	3	4	10
ANCHOVY	2	3	4	9
HERRING	2	3	4	9
MILKFISH	1	1	5	7
MULLET	2	1	4	7
RABBITFISH	1	1	4	6
TURTLE	5	5	5	15
EEL	5	2	5	12
OCTOPUS	4	3	5	12
BLOODWORM	3	5	3	11

NOTES (Information from Nash, 1974):
a. REFERS TO PRICE RANGE (ON A SCALE OF 1 TO 5)
b. BASED ON U.S. MARKET POTENTIAL (1 TO 5)
c. BASED ON FOREIGN MARKET POTENTIAL (1 TO 5)

Since water movement produced by waves are largely are a surface phenomenon and the water particles rotate in circular orbital motions, a submerged cage is also less susceptible to damage from waves than conventional cages. In deep water, the wave motion at a depth of one-half the wave length is almost negligible.

Optimal cage volume is believed to be approximately 4000 square meters; however, careful analysis based on the biological behavior of the particular fish species to be cultured must be considered. The cage should also be designed so that is is possible to operate it safely from the surface even under unfavorable weather conditions, which are common in the open ocean. The final design of a submersible cage system, including the number, size, shape, materials, mooring, and ballasting of cages will also depend on other integrated systems to be used in conjunction with the containment system.

It is anticipated that, in the future, cage-culture will become obsolete. The combination of economics and severe weather conditions lead to methods of passive containment. Passive containment is defined as a system that keeps fish in the vicinity of a desired area without the use of walls or cages. With any passive containment system there exists the possibility of losses due to emigration; however, systems can be established which require little maintenance and will attract and hold natural fishery resources (Brock, 1991).

Passive containment systems capitalize on the behavior of fish and include attraction to light, attraction to sound, and attraction to shelter. Pneumatic barriers (bubble fences) appear to have possible potential for open ocean mariculture applications. Assuming an enclosure several hundred meters in diameter could be deployed at a depth of 600 meters, the advantages of such a system would be numerous. The system would be survivable in any weather, no biofouling would occur, bubbles would automatically oxygenate the enclosed water column, surface waters would remain calm within the enclosure since the bubbles act as wave absorbers, and a degree of artificial upwelling could occur by entraining deep water with the rising bubbles. Futhermore, if hydrogen production systems were to be integrated with open ocean mariculture, the bubble fence concept would be an attractive use for the waste oxygen that this process produces (Hanson, 1974).

In the open ocean, maintaining relatively dense, artificially upwelled water at or near the surface is a major design and engineering challenge. The three ways to achieve surface retention are through physical containment or by lowering its density through dilution or solar heating. Creative engineering design, which makes efficient use of the natural energy fluxes available, are essential to establishing the feasibility of any artificial upwelling system. It is essential that any open ocean mariculture system maintain nutrient and/or temperature differential barriers to retain the stock.

The base of operations for an open ocean mariculture facility should be designed according to the type of species to be cultivated, containment methods, harvesting and processing needs, geographic location, and other appropriate factors (Ribakoff, 1974). Options can be listed as:

coral atolls,

bottom-supported structures, and

floating platforms.

Coral atolls occur naturally in many parts of the Pacific Basin and would require a minimum amount of modification and capital investment due to their natural morphology. Pacific Basin atolls can be grouped into six major chains: the Marshalls, Gilberts, Carolines, Marianas, Line Islands, and the Hawaiian Archipelago. Any development of mariculture in these areas should give serious consideration to the following advantages offered by atolls:

Enclosed basins or lagoons of various depths and diameters occur naturally in many cases.

Because of a volcanic foundation, atolls are usually in close proximity to deep water where phytoplankton nutrients are abundant.

Atolls are highly stable and survivable, and require mimimal maintenance.

Many atolls lie within inhabited island areas where some type of economic development is desired.

The majority of bottom-supported structures have been constructed by the offshore oil and gas industry. The basic design of these platforms consists of a flat deck, a supporting framework, and pilings or legs which are embedded or anchored in the sea floor. Since the platform is moored and rigid, it is considered to be highly stable and no motions other than vibrations resulting from wave impact are usually discernible on deck. The major disadvantage, with respect to offshore mariculture applications, is that this type of structure is generally limited to water depths of approximately 100 meters.

Floating platforms appear to be the most promising concept for offshore mariculture development (Bregman and Takahashi, 1993). This includes conventional ships and barges, as well as semisubmersible platforms. The chief advantages of semisubmersibles are a high level of motion stability and and high survivability in extreme environmental conditions. The major technical disadvantage results from the the fact that water-plane area is minimal giving relatively little buoyancy force per unit of submersion. Overturning moments and added loads must be compensated for by ballast adjustments, in contrast to the spontaneous compensation occurring in ships and barges (Ribakoff, 1974).

Another alternative, which is especially applicable for large structures in turbulent seas is indirect displacement. Indirect displacement with pneumatic stabilization has the following advantages over conventional direct displacement vessels (Innis, 1991):

simpler on-shore construction of smaller modules,

greatly reduced forces at module junctions,

reduced draft and mass,

greater ability to absorb impact loads, and

greater ability to utilize the energy causing destabilization.

The principle behind indirect displacement is that the vessel is supported on a compressible bubble of air rather than incompressible water. The bubble acts as a shock absorber to changes in the surface conditions of the ocean to mitigate pitch and heave.

Phillips et al. (1991) proposed to evaluate the feasibility of two potential oceanic mechanisms to help mitigate global warming: (1) enhanced carbon dioxide uptake via nutrient subsidy to marine algae and subsequent deposition in marine sediments, and (2) enhanced dimethyl sulfide production via marine algae to increase cloud formation and albedo. Two modeling tasks were identified: (1) a comprehensive oceanic model integrating the behavior and fate of greenhouse gases in the Northern Pacific Ocean subtropical gyre, and (2) a model developed by Madenjian and McKinley (1988) of nutrient cycles within oceanic cold-core rings. After these modeling activities and prior to implementing large- scale mitigation schemes, it is important to conduct baseline environmental research and controlled experiments to avoid deleterious impacts on the oceans (Phillips et al., 1988).

Regarding the carbon uptake hypothesis, the CO_2 concentration of the atmosphere has been increasing at about 1.5 ppm annually, which accounts for an accumulation of approximately 3 gigatonnes of carbon/year. If the application of a nutrient subsidy could enhance phytoplankton productivity such that 10% of the open ocean NPP (net primary production) is buried in deep-sea sediments (an order of magnitude higher than the one percent deposited under natural conditions), then 2 gigatonnes of carbon/year could be removed to mitigate the greenhouse effect. This amount would decrease atmospheric CO_2 concentration at a rate of about one ppm/year. By controlling the amount of fertilizer applied to the world's oceans, the temperature of the planet could thus be controlled.

Phillips et al. (1991) observed that with respect to dimethyl sulfide, a metabolic waste product of oceanic phytoplankton and the primary source of sulfate aerosol and cloud condensation nucleii in the remote marine atmosphere, an increase would enhance cloud formation and the subsequent albedo, which would reduce global temperature, marine algal productivity, and DMS emissions. Specifically, the global mean temperature might be reduced by 1.3°C through a 30% increase in albedo resulting from the biogenic sulfate/enhanced cloud formation mechanism. Artificial upwelling would serve to drive the equation towards higher algal productivity and thus higher equilibrium values for DMS. Ultimately, this negative feedback system may help regulate the Earth's climate.

6. Strategic Objectives and Plan of Action

The long-term development of ocean energy systems will no doubt depend on the future cost and availability of conventional fossil fuels. Should fossil fuel prices increase at the same rate as inflation, and externalities not considered to a much greater extent than they currently are in economic analyses, integrated systems will be neccessary. These will range from one megawatt and smaller, to ultimately, floating cities and industrial complexes powered by gegawatt size plants. While early systems for artificial upwelling might well use surge pumps, as there is sufficient nutrient content from depths of several hundred meters, OTEC appears to offer the best hope for an ocean alternative which could stabilize fossil fuel prices.

Through the remainder of this decade, system applications will follow the model operating at Keahole Point in Hawaii, land-based for power, freshwater, air conditioning and mariculture products. The next generation systems early in the 21st Century will move into the open ocean on floating platforms, where the cold water effluent will be mixed with the warmer surface water so that the high nutrient fluid can be maintained in the euphotic zone for photosynthesis. Closing the biological growth cycle will result in sea ranches and hatcheries for pelagic species such as tuna and mahimahi, and marine biomass plantations which can provide the feedstock for conversion to transportation fuels and high value chemicals.

An international partnership of industry, government, and academia to design, build and operate a very large floating structure powered by OTEC, which would also provide freshwater, air conditioning and artificially upwelled fisheries and marine biomass plantations; serviced by a variety of ocean robotics; demonstrating the feasibility of seabed ore and methane clathrate mining and processing at sea; advancing the prospects of tapping oceanic hydrothermal deposits; conducting tests to create new materials and sensors to withstand corrosion and deep ocean conditions; and serving as a marine scientific base for experiments and measurements would be an imaginative venture of commercial potential with possible environmental benefits.

Project Blue Revolution (PBR) has been proposed (Takahashi and Matsuura, 1991) to be the platform to undertake this integrative mission. Figure 14 shows the total program in a systems framework. The platform would be a grazing structure, estimated to cost $500 million, be ready for full operation early in the next decade, and coordinate the following projects:

1. marine science open ocean observatory;
2. environmental monitoring and assessment, including experiments to test the hypothesis that global warming can be remediated through a combination of artificial upwelling, and, perhaps, the supplementation of key minerals;
3. incubator facilities for new ocean industries;

4. baseline data for renewable energy powerplants and hydrogen production; and
5. base of operations for:
   a. marine biomass cultivation, harvesting and processing into bioalcohol for transportation fuel;
   b. seabed ore and methane clathrate exploration, mining and processing; and
   c. hydrothermal deposit experimentation for energy and minerals production.

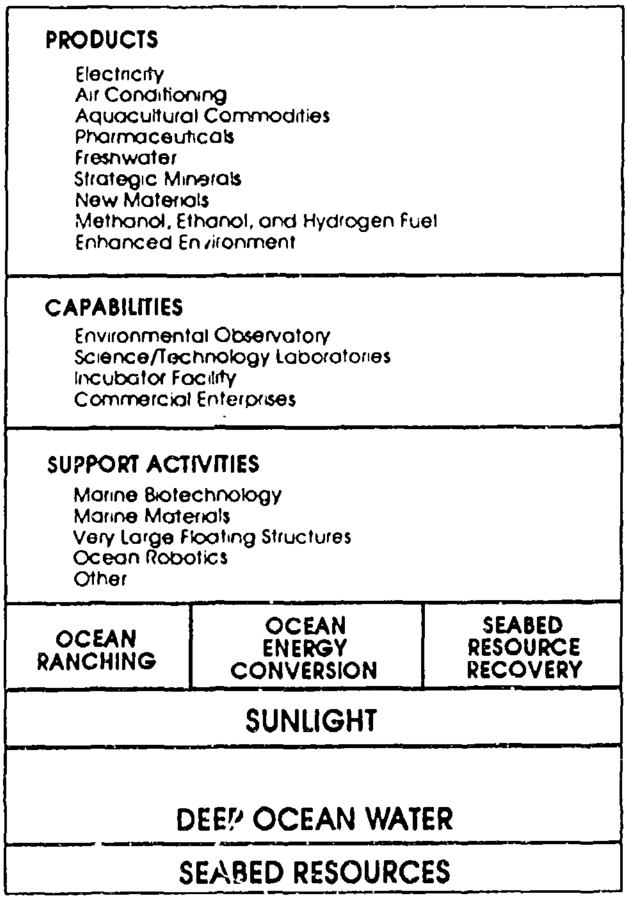

Figure 14. Project Blue Revolution (PBR)

As an international, multi-sector ocean resource applications project, Blue Revolution will greatly increase our understanding and utilization of the ocean frontier around us. The stimulus to be provided by PBR shows promise for materially advancing commercialization of the ocean in a manner compatible with the environment to produce food, energy and materials for mankind.

Installations of commercial OTEC plants at various sites throughout the world by the year 2005 are predicted. A combination of technical and economic factors create challenges in realizing the widespread commercial utilization OTEC systems.

To construct future plants as large as several hundred megawatts, as conceived by OTEC planners, much larger-diameter seawater pipes must be available. One proposed solution is the use of large pipes made of a flexible membrane that would be "inflated" by the positive pressure of seawater supplied by pumps mounted in the cold water zone on the sea bottom. However, bottom-mounted pumps present a difficult maintenance problem. Also suggested is the mounting of OTEC plants on "towers" resting on the sea bottom, which would serve as a framework for a very large-diameter pipe.

Much larger turbines than those in current usage will be required for use with the low-pressure steam of the OTEC process. These new turbines will have to be constructed of light weight, durable materials. PICHTR's research plan calls for testing innovative turbine designs.

PICHTR estimates high sales potential for 1 megawatt (net) OTEC plants for the tropical Pacific Ocean. However, financing methods for countries with marginal economies need to be worked out. One approach to financing OTEC projects in the Pacific region involves PICHTR's assistance to governments in gathering, verifying, and analyzing data to develop business plans for seeking financing from appropriate agencies.

Mariculture operations based on OTEC technology that can be economically viable must be thoroughly pursued. The potential to produce food products for local consumption and export will essentially lower the cost of operating an OTEC plant. Establishing mariculture operations in some island locations may be very inexpensive because the addition of nutrient-rich seawater to lagoons or bays could stimulate biological activity as well as attract marketable species from the open ocean.

A significant challenge lies in the logistics of deploying OTEC plants in remote locations. Some island communities have inadequate harbors, airports, and housing, and lack technical expertise in operation and maintenance and other elements needed to accommodate OTEC plant installation and operation. Plants could be delivered in a special OTEC deployment vessel containing all the components, equipment, and personnel necessary for complete installation. After the installation, local residents could be trained in operation and maintenance.

While the key to the commercial success of OTEC is not limited to cost effective power generation, nor the need for environmental incentives, all the other ocean energy options will require some combination of higher fossil fuel prices and externality benefits. The world trend seems headed in the direction of higher environmental sensitivities, as epitomized at the Rio Earth Summit and the growing concern about ozone depletion and global climate change. Yet, it remains unclear whether carbon or BTU taxes will ever be effectively legislated, for this is an item requiring world-wide acknowledgement and implementation. Symbolic victories amounting to up to 25% the cost of conventional fuels could be enacted, but even this differential will not be sufficient to stimulate widespread expansion of non-OTEC ocean energy.

Should, energy-related wars, major fossil fuel labor strikes and nuclear accidents (whether by accident or terrorism) occur with some regularity, and there is solid confirmation that the greenhouse effect is definitely warming the atmosphere, the following major ocean energy/resource projects can be anticipated by the year 2005:

1. Project Blue Revolution incubator plantship producing a wide variety of ocean energy and resource products.
2. South Korea tidal power generation of several hundred megawatts.
3. Italian Strait of Messina current power production approaching 100 megawatts.
4. Taiwan 50 megawatt OTEC plantship off the East Coast, with plans for 400 megawatts to be fed to the grid.
5. Scattered small OTEC facilities in island communities, with a total electrical production rate exceeding 100 megawatts.
6. Isolated wavepower applications in the total order of about 100 megawatts.

The combined electrical production at the end of the 1995-2005 period thus remains on the order of one nuclear powerplant. This might seem discouraging, but should not be the case, as the following forces will by then be set in motion:

1. Establishment of environmental incentives.
2. Elimination of bureacratic and financial roadblocks, clearing the way for utility and private investment in ocean options.
3. The creation of industry-government partnerships such as the recently established U.S. National Ocean Resource Technology Corporation, which on an international scale, will serve as the stimulus to plan for, finance, build and operate multi-billion dollar floating plantship options, many of them related to real civilian problems facing coastal cities, such as:
    a. processing of municipal wastes at sea, as part of a total system for reducing carbon dioxide disposal and producing hydrogen for commercial use;

b. removal of chemical and other industrial complexes near populated regions unto floating structures, where, again, cost effective mechanisms will be implemented to reduce environmental effects; and
c. creation of floating recreational sites and cities powered by various forms of ocean energy.

The decade revolving around the turn of the century can be a turning point, as there will be a clearer picture on the following:

1. Establishment of mechanisms to fund programs that previously went to support the Cold War towards to civilian applications and environmental enhancement.
2. The reality of global climate change and the ozone hole, and the steps which need to be taken to reverse the effect.
3. Recognition of the ocean (not space—which had a Cold War stimulus) as the next frontier for economic productivity, but in tune with nature.

Having developed the above scenario, serious planning will begin by 1995 to initiate the broad spectrum of ocean resource activities. By 2005, there will be a wide variety of ocean energy facilities generating electricity and powering integrated enterprises. Only then will large scale utility and commercial applications begin. Given the above turn of events, ocean energy options can become a major contributor to the mix of power sources by the year 2020.

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Summary

The oceans occupy nearly three-quarters of the Earth's surface and represent an enormous source of nonpolluting, inexhaustible energy. They provide a renewable energy resource that can be developed to reduce reliance on the combustion of fossil fuels and the resultant environmental problems of global warming and air pollution. The primary attraction of energy derived from ocean resources is the combination of largely benign effects on the environment and the guarantee that the resource base will be infinitely available.

Ocean energy research has concentrated on electricity production; however, secondary products from certain ocean energy systems significantly improve economic analyses of these systems. Ocean thermal energy conversion (OTEC) systems look especially promising because of the wide range of products potentially available. Small-scale systems providing electric power, nutrients for mariculture, and fresh water are ideal for expanding the economic potential of many island and coastal communities. This bridging option will enable the technology to mature, strengthen commercial utility, and enable progression to larger systems providing multiple products in addition to energy.

The OTEC concept was first proposed by the French engineer Jacques Arsene d'Arsonval more than a century ago. He envisioned a closed-cycle heat engine using ammonia as the working fluid, but never tested the concept. Almost fifty years passed before one of d'Arsonval's students, Georges Claude, designed and field-tested an experimental system at Matanzas Bay in northern Cuba in 1930. Although his model generated 22 kilowatts (kW) of power, it consumed more power than it generated. Claude later attempted a floating plant aboard a cargo vessel moored off the coast of Brazil. Waves destroyed the cold water pipe as it was being deployed, and Claude never achieved his goal of generating net power with an OTEC system.

The basic principle of OTEC involves the extraction of thermal energy from warm surface waters of tropical oceans to drive a cyclic heat engine. The heat engine transforms a portion of this energy to electrical power and rejects the balance to a colder, thermal sink. The thermal sink employed is seawater brought up from the ocean depths by means of a submerged pipeline. The two predominant OTEC heat engine cycles are the Rankine or closed-cycle, and the Claude or open-cycle. Although other techniques have been proposed to exploit the temperature gradient of tropical oceans to produce power, practical considerations suggest that near-term realization of OTEC lies in Rankine or Claude cycle plants.

When the oil embargo of 1973 prompted an international search for alternative sources of energy, the potential of OTEC was reexamined. In 1979 a closed-cycle Mini-OTEC plant produced net power, and closed-cycle heat exchangers were tested by a vessel designated as OTEC-1 in 1980. Both projects were conducted in Hawaii. Additional experiments in Hawaii at the Seacoast Test Facility of the Natural Energy Laboratory of Hawaii (NELH) on the western shoreline of the Big Island of Hawaii showed that cold deep ocean water is rich in nutrients and relatively pathogen free.

Commercial development has resulted from this work, and NELH added the Hawaii Ocean Science and Technology (HOST) Park for new enterprises to continue developing applications for the cold seawater. In the Spring of 1993, PICHTR, largely through U.S. Department of Energy and State of Hawaii funding, dedicated a 210 kW open cycle OTEC powerplant at NELH, the first net positive device of its type ever tested.

Tidal power is derived from the enormous energy induced in the oceans by the gravitational forces of the sun, moon, and earth. The ebb and flow of the powerful ocean tides are greatly influenced by inshore geological features. Tidal energy is generated by collecting rising tidal water behind a barrier and then releasing it at ebb tide through turbines to generate electricity. Systems are available to extract energy by relatively conventional hydroelectric turbines and related structures. Natural sites and celestial forces appear to favor the development of tidal power systems within latitudes of 50 to 60 degrees.

There are very few tidal energy power stations operating in the world today. The four countries with functioning systems are France, the Soviet Union, China, and Canada. These countries have been the most actively involved in the study of tidal energy conversion. The total power generated by these systems is about 263 megawatts (MW). The La Rance tidal power station on the west coast of France, with an installed capacity of 240 MW, is the world's largest ocean energy development. Construction began in 1961 and was completed by 1968. The plant has been operational since 1968 with an outstanding 95% availability. South Korea has recently proposed a major new project.

Ocean wave energy conversion technologies utilize the kinetic energy of ocean waves to produce power. Wave energy is a potential environmentally benign and renewable energy resource. The general approaches to converting wave energy into electricity can be broadly categorized by means of deployment and means of energy extraction and conversion. Deployment concepts include floating deep-water technologies and shallow-water, fixed-bottom technologies. Energy extraction and conversion options include mechanical cams, gears, and levers; hydraulic pumps; pneumatic turbines; oscillating water columns; and funnelling devices. At present, five wave energy systems generate a total of 535 kW of power, and two more commercial systems are planned for the near future.

The Japanese government has had a very active wave energy research and development program for many years. Applications under investigation range from wave power generators for lighthouses and light buoys to wave pump systems, ship propulsion, and energy for road heating, heat recovery systems, and fish farming. Several technologies have been examined by both government and industry under the Japanese wave energy program. These include floating terminator-type wave devices, fixed coastal-type wave power extractors, and applications of oscillating water column turbines. The most well known project, supported by the International Energy Agency, was the Kaimei, a 500-ton barge-like platform containing about ten oscillating water columns.

Norway has conducted an extensive wave power program since 1975. In the 1980s, these efforts included the installation by Kvaerner Brug of a 500 kW prototype wave power system, called the multiresonant oscillating water column (MOWC), on the west coast of Norway. Operational since November 1985, the plant was swept off its foundation and destroyed during a severe storm in January 1989. In 1986, the Norwegian firm Norwave, installed a new system called Tapchan, a tapered channel wave power plant in Bergen, that produces 350 kW of power.

The kinetic energy of river currents has been used from medieval times to produce power using simple water turbines. There are many old prints that show mechanical power produced from mills at bridges to pump river water to the adjacent communities. The proposed application of current turbines in the oceans is a comparatively recent development, and has been prompted by the observations of mariners and oceanographers of the swiftly-flowing current in some regions of the world. The Gulf Stream, or more specifically, the Florida Current, is of particular interest because of the high current velocity and its proximity to large centers of population on the Florida coast. A feasibility study regarding the utilization of currents in the Strait of Messina in Italy was recently completed.

A large unused source of energy exists at the interface between freshwater and saltwater, and the extent of energy depends on the salinity gradient. In extracting this salinity gradient energy, the heart of most systems is a semi-permeable membrane that allows water, but not dissolved solids, to pass through the membrane. With freshwater on one side and saltwater on the other side of the membrane, the force of the freshwater through the membrane creates an osmotic pressure difference. As freshwater permeates through the membrane, a head of water is developed with respect to the saltwater, and a turbine can be used to extract energy from the water flow.

The mid to long-term potential of ocean energy appears to rest with multi-purpose integrated systems. These systems will range from less than one megawatt in size to floating cities and industrial complexes powered by large plants with outputs of several gigawatts. Through the remainder of this decade, systems development will follow the model operating at Keahole Point in Hawaii; land-based for electrical power, freshwater, air conditioning and mariculture products.

The next generation systems in the 21st Century will move into the open ocean on floating platforms, where the cold water effluent will be mixed with the warmer surface water so that the high nutrient fluid can be maintained in the photic zone for photosynthesis. Closing the biological growth cycle will result in ocean ranches and hatcheries for pelagic species such as tuna and mahimahi, and marine biomass plantations which can provide the feedstock for conversion to transportation fuels such as methanol and high value chemicals.

An international partnership of industry, government, and academia to design, build and operate a very large floating structure, powered by OTEC, providing freshwater, air conditioning and artificially upwelled fisheries and marine biomass plantations, and serving as a marine scientific base for experiments and measurements has been proposed as Project Blue Revolution. In addition, the National Ocean Resource Technology Corporation has been established in the United States, and the Floating Structures Association in Japan has been formed to promote floating platform concepts.

Installations of commercial ocean energy plants at various sites throughout the world by the year 2005 look promising. However, a combination of technical and economic factors needs to be resolved to stimulate the widespread commercial utilization of these systems. A significant challenge lies in the logistics of deploying equipment in remote locations. Some island communities have inadequate harbors, airports, and housing, and lack technical expertise in operation and maintenance and other elements needed to accommodate plant installation and operation. The growing sensitivity to environmentally compatible energy options, as well as the ending of the Cold War and the subsequent shift in emphasis from military to civilian applications, and key technological breakthroughs provide considerable optimism for major advancement in ocean energy development into the next decade.