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ABSTRACT

This report presents the environmental problems which may arise with the further development of Ocean Thermal Energy Conversion, one of the eight Federally-funded solar technologies. To provide a background for this environmental analysis, the history and basic concepts of the technology are reviewed, as are its economic and resource requirements. The potential effects of this new technology on the full range of environmental concerns are then discussed in terms of both their relative significance and possible solutions. Although the emerging solar technologies will contribute to environmental problems common to any construction project or energy-producing technology, only those impacts unique to the solar aspects of the technology are discussed in depth here. Finally, an environmental work plan is presented listing research and development proposals and an NEPA work plan which might help clarify and/or mitigate specific environmental concerns. (Author/MR)

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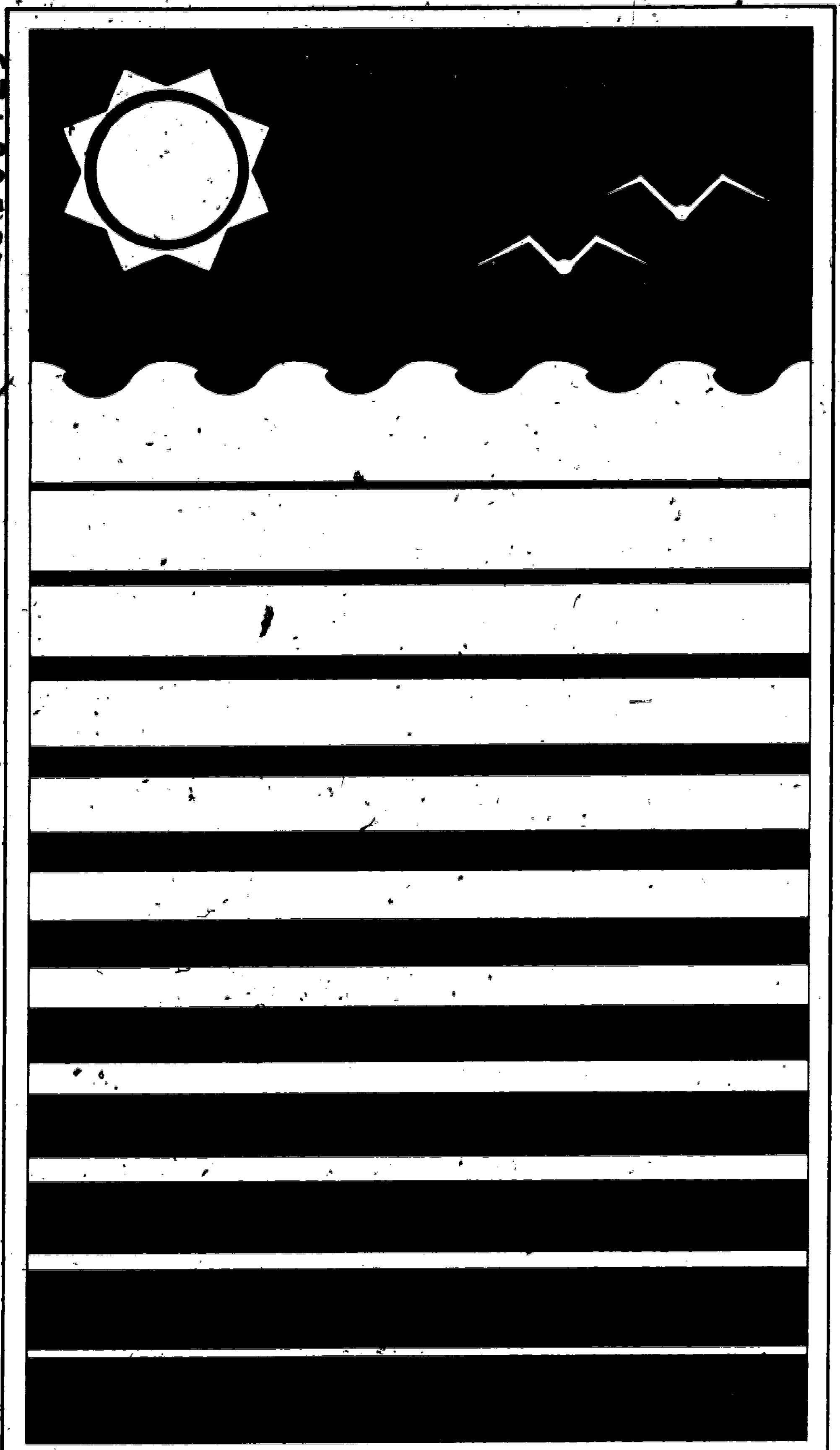

SOLAR PROGRAM ASSESSMENT: Environmental Factors

Ocean Thermal Energy Conversion

Environmental & Resource Assessments Branch

Division of Solar Energy

Energy Research & Development Administration
Washington D.C. 20454

March 1977

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INTRODUCTION AND ENVIRONMENTAL SUMMARY

A. Organization and Intention of Report

This report presents the environmental problems which may arise with the further development of Ocean Thermal Energy Conversion (OTEC), one of the eight Federally-funded solar technologies. To provide a background for this environmental analysis, the history and basic concepts of the technology are reviewed, as are its economic and resource requirements. The potential effects of this new technology on the full range of environmental concerns (i.e., air and water quality, biosystems, safety, social/institutional structures, etc.) are then discussed in terms of both their relative significance and possible solutions. Although the emerging solar technologies will contribute to environmental problems common to any construction project or energy-producing technology (e.g., air pollutants from steel production), only those impacts unique to the solar aspects of the technology are discussed in depth here. Finally, an environmental work plan is presented listing research and development proposals and a NEPA work plan which might help clarify and/or mitigate specific environmental concerns.

B. Environmental Concerns

1. Potentially Toxic Effects of Metallic Elements

One serious environmental problem posed by the operation of an OTEC plant is the potentially toxic effect on marine life of metallic elements eroded/corroded from heat exchangers. One side of an OTEC plant's heat exchanger surface will be continually subjected to the erosive and corrosive forces of sea water flow, causing a certain quantity of metallic elements to be continually dispersed into the ambient sea water. Depending on the material used to construct heat exchangers, these elements may have a toxic effect on marine organisms. Erosion/corrosion of a 90/10 copper-nickel exchanger, for instance, might cause serious ecological problems. If aluminum were used, toxic effects would probably be lessened, although little is known of the toxic effects of aluminum on specific marine organisms. The use of titanium as the heat exchanger material may cause even fewer environmental problems, since it is highly corrosion-resistant. Finally, if plastics can be developed for heat exchanger use, this particular toxicity problem may be obviated altogether.

2. Potential Ecological Impacts of Ocean Water Mixing

In an OTEC plant vast quantities of cold, deep ocean water are continuously pumped to the condensers near the ocean surface; a similar amount of warm surface water is also pumped through the evaporators. This artificial mixing of natural thermoclines, salinity gradients, and biotic species near an OTEC plant could have an adverse effect on local marine ecosystems. For instance, marine biota pumped up from deeper water will experience both a temperature increase and a pressure drop; surface organisms passing through the evaporators will experience a temperature decrease. Furthermore, the temperature of surface ocean waters surrounding an operating OTEC plant may be lowered a few degrees below previously normal levels, depending on where the plant is sited. Since lower surface water temperatures would degrade plant efficiency, computer modeling studies will indicate water discharge patterns and methods which would alleviate this potential problem; while laboratory tests and literature searches will help determine the extent to which typical biosystems would be impacted by pressure, temperature, and salinity changes. On the other hand, the artificial upwelling of deep ocean water may have positive consequences. The nutrient-rich cold water pumped to the surface may help establish commercial kelp farms or fisheries by enhancing biological growth in the vicinity of OTEC plants.

3. Potentially Toxic Effects of Working Fluid Leaks

Since in each OTEC plant millions of square feet of heat exchanger surface area will be subjected to physical and chemical stresses, leaks may develop in the exchanger surfaces, allowing the working fluid to seep into the seawater. Since OTEC plants will be equipped with inventory-monitoring devices, any significant leaks would be detected. If ammonia (the most likely working fluid candidate) were used, the environmental impact of small leaks (less than 1 percent of total inventory each day) would probably be negligible, since the seawater flow would dilute the ammonia considerably. However, since much larger spills are possible (for example, if a ship were to collide with an OTEC plant), dispersion modeling could be used to determine the probable extent of ocean area impact. The specific effects on local marine species impacted by a large-scale working fluid spill could be determined by laboratory testing.

4. Potential Ecological Impacts of Biocides

Chlorine has been suggested for use as a biocide to prevent biofouling on the seawater side of heat exchanger surfaces. Although proposed initial concentrations in an OTEC plant are 10-50 times greater than EPA's acceptable limit for marine waters, those concentrations would be diluted quickly by ambient sea water beyond the immediate discharge area of an OTEC plant. The rate of dilution could be determined by dispersion modeling; laboratory studies would help determine which marine species would be affected and to what degree by the chlorine discharge. This potential problem may be circumvented altogether by the use of mechanical cleaning devices (e.g., the periodic passage of rubber balls through heat exchanger tubes), anti-biofouling chemical coatings on exchanger surfaces, or the possible manipulation of heat exchanger surface properties. However, mechanical cleaning devices probably will not work if potentially more efficient plant-and-fin heat exchangers are used.

5. Potential Worker Safety Problems

The use of different chemicals in OTEC plants (e.g., ammonia or propane as a working fluid, chlorine as a biocide) could endanger the safety of construction, operation, or maintenance personnel. For instance, a mildly toxic gas is produced when ammonia is combined with seawater. On the other hand, ammonia's strong odor below toxic levels would provide a warning of possible danger. The possibility of fires or explosions would be especially serious if propane were chosen as a working fluid, which seems unlikely at the present time. However, safety procedures and guidelines would have to be established to govern the use of any potentially dangerous chemicals aboard an OTEC plant.

6. Potential Climatological Impacts of Lowered Sea Surface Temperatures

An OTEC plant's artifical upwelling of vast quantities of cold, deep water may lower by a few degrees the surface temperature of the ambient ocean. A slightly lower ocean surface temperature may lead to a slightly lower local air temperature. Anomalies in the local microclimate caused by the operation of a single OTEC plant may be significant, depending on the site chosen. The climatological impacts of several plants operating in the same general ocean area may be even more serious, although impacts will be limited by the need for each plant to maintain adequate temperature differentials.

7. Social and Institutional Impacts

Because OTEC components could be built on shore in existing coastal shipyards using existing construction techniques and materials, especially those typical for deep oil drilling rigs, the development of OTEC systems should have few social impacts beyond those associated with any large construction project. However, deep-water protected areas near deployment sites likely will be required for final assembly, causing transportation and support problems typical for any deep-water construction project. Some OTEC plants may contribute base-load electricity to existing grids, but they should have few unique impacts on utilities. However, exploitation of thermal resources in ocean areas beyond the jurisdiction of an individual nation may introduce problems regarding the rights, responsibilities, and liabilities of installing and operating energy-producing plants in international waters.

SECTION II

TECHNOLOGY

A. History of Technology

The basic thermodynamic law underlying ocean thermal energy conversion (OTEC), a process for producing energy from the difference in temperature between surface and deep sea water, was promulgated more than 150 years ago. Almost a century ago, the principle was related specifically to the use of sea water as a power source, and full-scale demonstration power plants have been built within the last 50 years. Although an OTEC plant has never produced electricity commercially, its operating principles have been clearly defined and technically demonstrated.

In 1824, Sadi Carnot, a French engineer, wrote in his Reflections on the Motive Power of Heat:

> The production of motion in the steam engine is always accompanied by a circumstance which we should particularly notice. This circumstance is the passage of caloric from one body where the temperature is more or less elevated to another where it is lower.... The motive power of heat is independent of the agents employed to develop it; its quantity is determined solely by the temperature of the bodies between which, in the final result, the transfer of the caloric occurs.

In other words, man's ability to convert heat energy into mechanical energy in any heat engine is limited not so much by the temperature of the heat source as by the difference in temperature between the heat into and the heat out of the engine. The difference in temperature is the real source of power, and the efficient transfer of heat within the engine the most important question: Carnot's studies established that, at least theoretically, any difference in temperature could be used to generate power.

Just over 50 years later, the ability of "natural forces" to produce electricity was debated theoretically in the pages of a French magazine, La Revue Scientifique.[1/] In the September 17, 1881, issue, Jacques d'Arsonval utilized Carnot's principle to hypothesize a process for producing temperature gradient power. He suggested operating a closed system in which a working fluid, possibly liquid sulfur dioxide, would be vaporized by the warm (30°C) waters of the spring at Grenelle, then condensed by colder (15°C) river water, the resulting pressure drop across the system providing a constant source of power. He noted that many places in the world could furnish the necessary temperature differential. Ideally, the evaporator could be immersed in the equatorial seas and the condenser at the poles, but he noted that the equatorial seas alone might suffice, since the temperature 1000 meters below the surface was 4°C.

D'Arsonval's student and friend, Georges Claude, verified d'Arsonval's hypothesis experimentally before the French Academy of Sciences on November 22, 1926, when his thermal gradient engine produced three watts of power to light three small lamps.[2/] Claude preferred water in an open system over sulfur dioxide or any other gas in a closed system, because it was cheaper and he felt it would transfer heat more efficiently through the inevitably dirty walls of his boilers. After his initial experimental success, he proceeded to build a 60 kW plant in the industrial complex at Ougree-

Marihaye, near Liege, Belgium. By June, 1928, he succeeded in producing electricity utilizing the 20°C difference between the water of the Meuse River and the cooling water of blast furnaces.

Buoyed by his continued success, Claude decided to build an experimental OTEC plant in the tropics to take advantage of greater temperature differentials and inexhaustible supplies of sea water. On the coast of Matanzas Bay, 100 kilometers east of Havana, Cuba, he built a powerplant that by the fall of 1930 was producing 22 kW of power.[3/] However, Claude was able to drop his cold water pipe only 700 meters below the surface of the sea. The resulting temperature differential of only 14°C, the low vapor pressure of sea water, deployment problems with the cold water pipe, and temperature fluctuations in the Gulf Stream caused Claude to shut down his plant. Although Claude's Cuban OTEC plant was economically inefficient (Cuban electricity was purchased to help run the pumps), the ability to produce electricity from ocean temperature gradients had been clearly demonstrated.

After he left Cuba, Claude's enthusiasm for the temperature gradient power principle continued unabated. He hoped to overcome some of the engineering and environmental problems he encountered in Cuba by building a power unit aboard the 10,000 ton steamer, Tunisie, with which he hoped to produce 800 kW. He stationed the ship off the coast of Brazil in 1934, dropped his cold water pipe into the waters beneath, and, after a lengthy series of technical and personnel problems, finally operated history's first ocean-going OTEC power plant.[4/]

Other French scientists carried on Claude's ideas and his work. Further research led to the formation in 1948 of "Energie des Mers" for the explicit purpose of building an OTEC power plant on the African Ivory Coast at Abidjan.[5/] French scientists hoped their 7000 kW shoreline power plant would utilize an offshore temperature differential of 20°C to produce both power and potable water. Construction was begun in the early 1950's, but the project was hindered by many of the same technical problems that beset Claude in Cuba: the immersion of a large diameter pipe in deep ocean water, intake of fauna in the cold water pipe, corrosion, power loss in pumps, and inefficient temperature differentials. The French finally abandoned the project in favor of a cheaper hydroelectric plant.

After the initial 100 years of sporadic investigation into and experimentation with ocean thermal energy conversion, mostly by French scientists and technicians, the U.S. Federal government became interested and involved in the early 1970's. Spurred on by increasing energy demands and dwindling energy resources, the Federal government began allocating increasing sums of money for research into all phases of solar energy. Ocean thermal energy conversion was first funded in FY 72 for $84,000, followed by $230,000 in FY 73, $730,000 in FY 74, $3,000,000 in FY 75, $6,000,000 in FY 76, and $2,400,000 in the transitional quarter.

Federal funding for OTEC research probably will continue to rise during the next several fiscal years. According to ERDA's Program Approval Document For Solar Energy Development (March 5, 1976), $9.2 million are projected for FY 77, $26.1 million for FY 78, $85.3 million for FY 79, and $231.6 million for FY 80.[6/]

Increased Federal monies have nurtured increased involvement by the American academic and industrial communities. The first public OTEC workshop, convened to review the status of the national OTEC program, was held at Carnegie-Mellon University (CMU) in June, 1973;[7/] the second was held in Washington, D.C., in

September, 1974.[8/] At the third and latest workshop, held in Houston in May, 1975, 150 representatives of industry, universities, and government met to present, listen to, and discuss more than 30 technical reports on various aspects of OTEC technology.[9/]

1

B. Basic Technological Concepts

1. Introduction

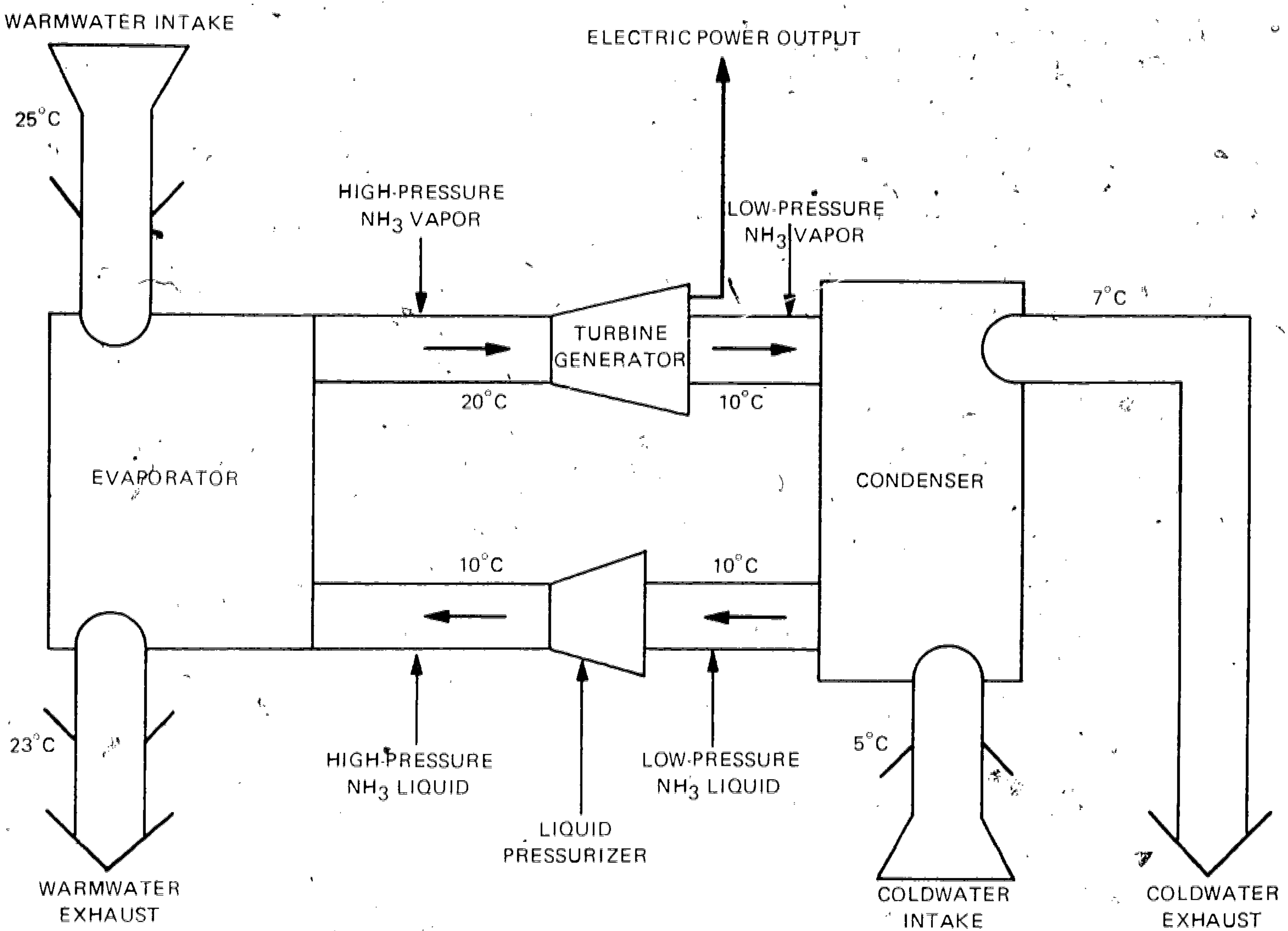
The basic operating principles of an OTEC powerplant have remained unchanged since d'Arsonval proposed them almost 100 years ago. The ocean is for all practical purposes an infinite heat source, converting and storing the incident solar energy from the sun in the form of warm surface water. The warm water is pumped through an evaporator containing a working fluid in a closed Rankine-cycle system. The vaporized working fluid drives a gas turbine which provides the plant's power. Having passed through the turbine, the vapor is condensed by colder water drawn up from deep in the ocean and then pumped back into the evaporator for re-use in the same cycle. No "fuel" of any kind is used; the enclosed working fluid simply is evaporated and condensed over and over by the warm surface and colder deep ocean water (see Figure II-1).

The open Rankine system tested by Claude operates in much the same way, except sea water itself is used as the working fluid, obviating the need for heat exchanger surfaces. Warm surface sea water flows into an evacuated evaporator where the lowered pressure causes it to boil. The steam produced passes through a turbine, after which it is condensed by cooler ocean water. Again, no "fuel" is used.

However, although OTEC operating principles are simple and well known, both the closed and open cycle systems pose complex engineering and cost problems. In both cases, the small temperature differentials (approximately 40°F vs. 1000°F in coal-fired boilers) dictate that large quantities of water must be pumped, the pumping power being subtracted from the net power of the system. Additionally, the closed system faces problems in efficiently transferring heat over large surface areas, while construction and maintenance of large

FIGURE II-1

SCHEMATIC DIAGRAM OF OTEC POWER CYCLE



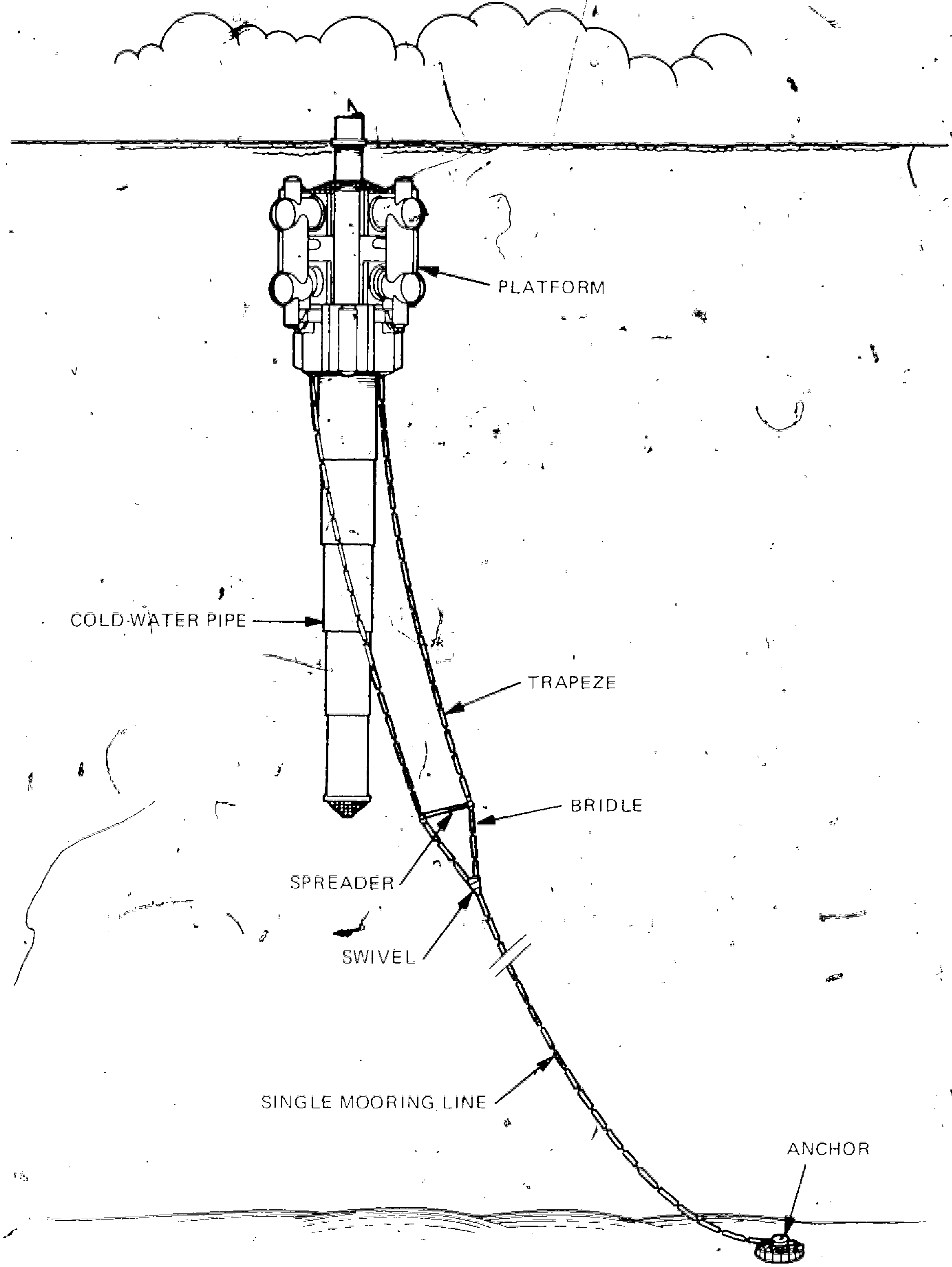
SOURCE: EEA, Inc.

vacuum enclosures and the design and manufacture of low pressure vapor turbines with rotor diameters on the order of 100 feet are needed for the open system.

Several different research teams have been working to overcome the problems of both closed and open systems. One of America's OTEC pioneers, J. Hilbert Anderson, and his son, James H. Anderson, Jr., have been publishing their OTEC studies since the mid-1960's and have formed Sea Solar Power, Inc., to advance work on a closed OTEC system. Clarence Zener, who also worked on OTEC systems during the 1960's, is currently with a team at Carnegie-Mellon University which has been studying conceptual designs for OTEC system components. A University of Massachusetts/Amherst team has been studying OTEC possibilities in the Gulf Stream off Miami, Florida, since the early 1970's, while Johns Hopkins University's Applied Physics Laboratory (APL) has been assessing OTEC's engineering and economic feasibility. Two industrial teams, Lockheed and TRW, have prepared studies of complete hardware systems for OTEC power production at sea using state-of-the-art technology and current material and product prices.[10/11/] (See Figures II-2 and II-3 for drawings of Lockheed and TRW models.)

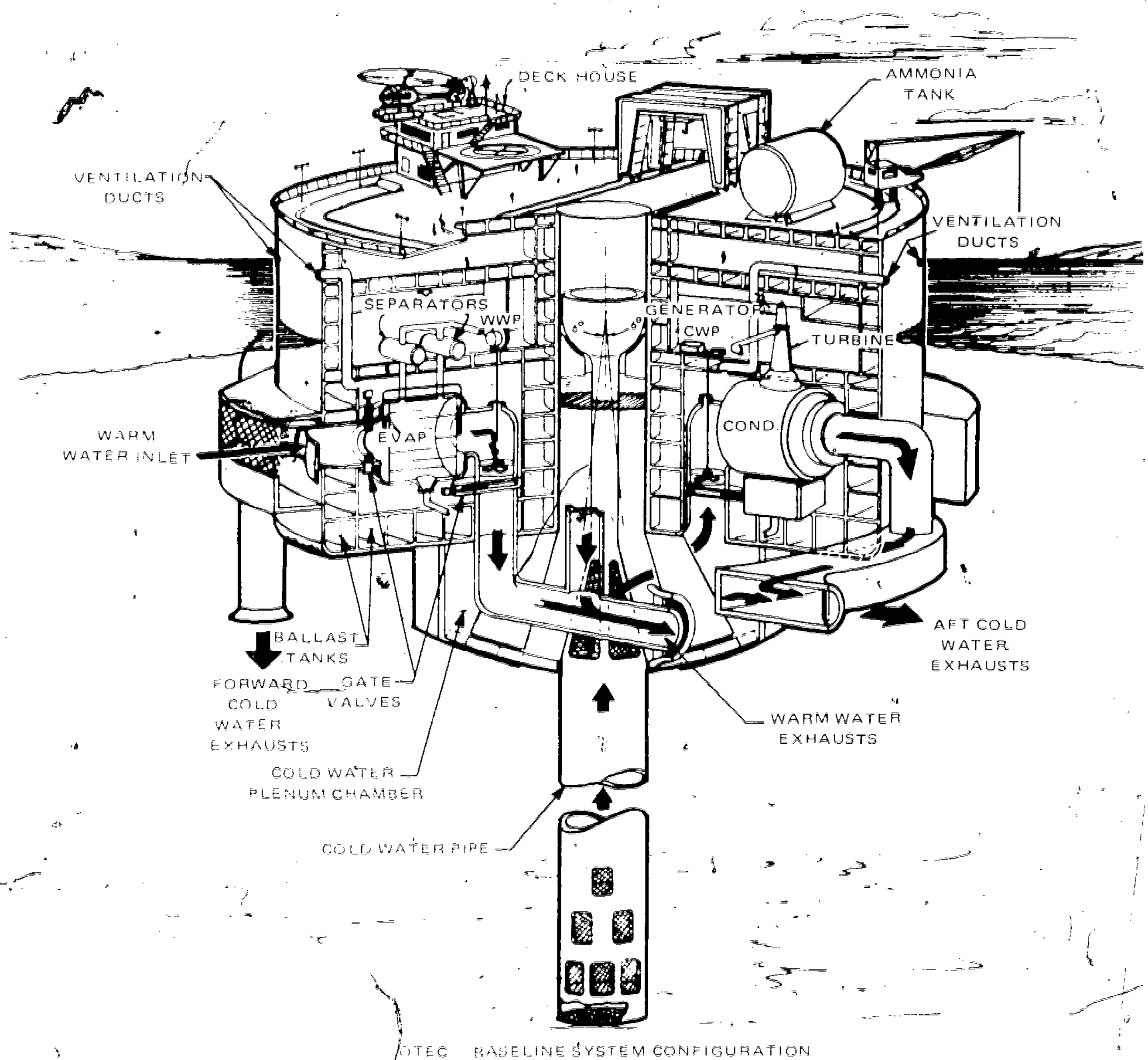
Although closed cycle OTEC systems seem to hold the most promise for the immediate future, current research is also being carried out on the open system. Hydroynautics, Inc., has been studying the engineering feasibility and probable costs of an open-cycle OTEC system utilizing falling film direct contact evaporation and condensation. An open-cycle system using low-pressure steam has been proposed;[12/] a modification has been suggested to utilize foam instead of water vapor or liquid.[13/] Finally, the Colorado School of Mines has been involved in a study of turbines applicable to open-cycle OTEC systems.

FIGURE II-2
FULL VIEW OF LOCKHEED OTEC PLANT MODEL



SOURCE: Lockheed Missles and Space Company, Reference 10.

FIGURE II-3
CUTAWAY VIEW OF TRW OTEC PLANT MODEL



SOURCE: TRW Systems Group, Reference 11.

2. Heat Exchangers

If closed cycle systems are to become increasingly feasible both technologically and economically, OTEC proponents point out that further intensive engineering development must be carried out in several key areas, the most important being heat exchanger design and construction.

The heat exchangers are probably the single most important component of an OTEC system, both in terms of operating efficiency and cost-effectiveness, since the efficiency of the heat exchangers in transferring heat from the water to the working fluid and vice versa will significantly affect plant operation. The measure of a heat exchanger's ability to perform efficiently is its heat transfer coefficient, U, measured in Btu/hr-ft^2-^{o}F. U is a function of both construction material and design, and it is further influenced during operation by exchanger resistance to corrosion, erosion, and biofouling by marine organisms. In terms of cost-effectiveness, however, the optimum heat transfer coefficient must be weighed against the initial cost of exchanger materials and construction and their expected longevity.

Several different materials have been considered for heat exchanger construction, but presently only four seem to be realistic possibilities: titanium, aluminum, 90/10 copper-nickel, and plastic.

Titanium is being seriously considered as a heat exchanger material because of its excellent resistance to sea water corrosion and its ability to withstand high water flow velocities without eroding. Its strength and durability also recommend it, since thinner tube walls would allow easier heat passage, and longer tube life would minimize maintenace, repair, and replacement costs.

However, titanium poses potential availability and cost problems. Although titanium is the ninth most abundant metal in the crust of the earth, American industry currently has the capacity to produce only 18,500 short tons of titanium per year.[14] Consequently, current titanium prices are higher than those of the other heat exchanger material candidates. However, titanium production could be increased markedly with known technology, thereby reducing cost and increasing availability.

Because of titanium's current cost and possible availability problems, aluminum has been suggested as an alternative. It is now cheaper and much more plentiful, but it is structurally weaker and more susceptible to sea water corrosion. It has a shorter life expectancy in an undersea environment, but lower initial costs may compensate for later replacement costs.

The 90/10 copper-nickel alloy being considered as a heat exchanger material has been extensively used in both land-based and shipboard power plant condensers using sea water as a coolant. Since in its ionic state it is toxic to certain marine life, it would probably inhibit biofouling effectively in the heat exchanger tubes. This advantage, however, would have to be weighed against its potentially toxic effects on marine life in the ambient ocean waters. Copper-nickel also resists corrosion due to seawater very well; however, seawater mixed with ammonia could corrode copper-nickel surfaces extensively. Because of copper's incompatibility with ammonia, the most likely OTEC working fluid, its use as a heat exchanger material may be precluded.

Heat exchangers may also be fabricated from plastic, if technical problems unique to the use of plastic can be overcome. For instance, the single plastic resin or combination of resins best suited to long-term underwater use must be found. Furthermore, since thermal conductivity must be maximized, special graphite-filled, multi-layered plastic materials may be used to enhance the thermal and hydraulic properties of plastic exchanger surfaces. If a plastic material can be developed to withstand the stresses of use in heat exchangers, OTEC plant capital costs may be decreased significantly.

The final decision on heat exchanger materials will be influenced to some extent by exchanger design and vice versa. Two basic designs are under consideration: shell-and-tube and plate-and-fin. The shell-and-tube exchanger seems the most viable at the moment, since it is widely used in industrial heat exchange operations. Plate-and-fin exchangers, on the other hand, have not been built on the scale needed in an OTEC plant.

3. Biofouling Control

Although it is not clear to what extent marine organisms will foul the sea water side of heat exchanger surfaces, the potential for inefficient heat transfer due to underwater biofouling has led to extensive research on both the extent of biofouling to be expected and different methods of counteracting it. Biofouling effects will be less severe in the condensers than in the evaporators, since cooler, deeper water is much less conducive to microscopic life than warmer surface water. However, any biofouling will be unsatisfactory, since maximum heat exchange is the life principle of an OTEC plant.

The selection of a site will influence the degree to which biofouling affects plant operation. Although marine biota are more dense in coastal waters due to the increased nutrient content of land runoff, an OTEC plant operating in the open ocean may also be affected. Nutrient enrichment caused by artificial upwelling will promote biofouling no matter where OTEC plants are sited. Particular sites will have to be tested individually to ascertain the specific types and concentrations of marine organisms present. The water at the candidate sites must also be sufficiently deep so that the cold water pipe will not draw organism-rich water from near the ocean floor. Moreover, certain biota may adhere to heat exchanger surfaces in the event of flow shutdown (i.e., during storms and maintenance, etc.). They would have to be removed before operations resumed.

Biofouling problems can be curbed somewhat by regulating the flow of water through the exchanger system. At a sea water flow of 6 ft/sec, organisms have more difficulty attaching themselves to the tube walls than at slower speeds. OTEC researchers are also studying chemical (chlorination), mechanical (the use of brushes or rubber balls), and material (exchanger surface coatings) means of preventing biofouling.

4. Working Fluid

The choice of the best possible working fluid for the closed system is also important for the development of OTEC power plants. The fluid must not only have the heat transfer characteristics and thermodynamic properties necessary for efficient energy conversion, but it should also be compatible with the material chosen for heat exchanger construction, readily available at a reasonable cost, safe to work with, and non-toxic to the environment in case of a leak.

Three fluids have been seriously considered for use in OTEC power plants: ammonia, propane, and the fluorocarbon R 12/31. However, R 12/31 has demonstrated the poorest thermal characteristics of the three and the National Marine Fisheries Service has noted that besides posing potential dangers to marine life if leaked into the ocean, it may escape into the atmosphere where it could tend to destroy the protective ozone layer. [11/] Consequently, ammonia and propane are the leading candidates for OTEC working fluid use, and the final decision will probably be influenced by the heat exchanger material chosen.

Propane is being considered because of its low cost and high density at operating conditions and its relatively low corrosive effect on potential heat exchanger materials. Ammonia, on the other hand, is highly corrosive to copper and copper alloys. Yet ammonia's working characteristics are superior to propane's. It has a much higher thermal conductivity and heat of evaporation, and only a slightly lower heat capacity. Since it is less flammable than propane, it poses fewer safety hazards. Furthermore, an ammonia leak into the ocean may have only a temporary local effect, since it is highly water soluble. Sufficiently diluted, it may even serve as a nutrient for marine biota.

5. Energy Utilization

The energy produced by an OTEC plant has to be transmitted to consumers and, for a powerplant floating some distance at sea, solutions to the transmission problem may be complex and expensive. However, if OTEC plants can produce electricity cheaply enough, consumer savings in energy costs will compensate for any added costs of transmission.

An OTEC plant will generate alternating current; most land-based power users demand alternating current. Therefore, the energy transmission problem could be solved simply by connecting the power plant to the utility via an underwater AC umbilical cable. For short distances (less than 20 miles), an AC ocean-to-land hook-up may be economically feasible. At distances greater than 20 miles from shore, AC transmission losses plus the cost of the third conductor necessitated by alternating current indicate that direct current transmission may be economically and technically more feasible. However, DC transmission will incur a cost penalty for the power-conversion equipment needed at both ends of the underwater cable.

At some distance from land, however, the transmission of electrical energy via underwater cable will become prohibitively expensive. Therefore, other means of utilizing OTEC produced electricity will have to be developed.

Electricity in an ocean environment can be used to produce different energy intensive materials, provided the electricity is cheap enough to make the processes economically feasible. For instance, sea water could be electrolyzed to make hydrogen; liquified hydrogen could then be shipped by tanker to consumer ports for use in hydrogen power cells.[15/] Liquid oxygen may be a valuable by-product of the hydrogen-producing process. Nitrogen from the ambient air could be added to the hydrogen to produce ammonia, which presently is in greater demand than liquid hydrogen. Electrolysis of sea water may produce significant quantities of chlorine, caustic soda, and magnesium. Furthermore, if the necessary raw materials can be transported to the OTEC plant, the electricity could be used to produce aluminum from bauxite or liquid natural gas from coal. Any of these energy-intensive products could be shipped directly from an OTEC plant to markets anywhere in the world. Therefore, since OTEC plants may be sited near potential markets, the cost of transporting either raw materials or their products may become a less important consideration.

6. Site Specification

The identification of adequate sites will be an important step in the development of OTEC's potential. Since OTEC depends on the difference in temperature between surface and deep ocean water, a specific site must demonstrate a temperature differential sufficient to guarantee efficient plant operation year round. A number of such sites can be found world-wide between $\pm$ 20° of the equator.[16/]

Furthermore, it has been estimated that plant costs are affected exponentially by the temperature differential:[17/]

$$C_1 = \left(\frac{\Delta T_2}{\Delta T_1}\right)^{2.5} C_2$$

Where C_1 = cost at site 1
C_2 = cost at site 2
ΔT_1 = temperature difference at site 1
ΔT_2 = temperature difference at site 2

This cost impact is caused principally by the smaller amounts of exchanger material needed at sites with greater temperature differentials. Therefore, a specific site must be chosen before a plant's costs can be accurately predicted.

Finally, both the environment's effects on the plant and the plant's effects on the environment will have to be considered. Low current, wind, and wave velocities are desirable for stable plant mooring and/or positioning, but high current velocities would aid in the dispersal of effluent waters. Major storm areas should be avoided. On the other hand, the impact of OTEC operations on the local ecology will also have to be considered in the selection of OTEC sites.

SECTION III

ECONOMICS AND MATERIAL REQUIREMENTS

A. Introduction

Since neither a demonstration nor a prototype OTEC powerplant has yet been built in the U.S., the economics of the system are somewhat uncertain. Even though the heat exchangers, for instance, are the single most expensive subsystem of an OTEC plant, accounting for 50-70 percent of the total initial capital outlay, OTEC researchers have not yet reached a consensus of opinion on the design or materials to be used. Furthermore, until a specific site is chosen, the economic effects of the available temperature differential, its fluctuations over a year, and local biofouling will be difficult to determine precisely. More component testing and laboratory modeling are needed in order to develop more exact cost estimates.

B. Costs

Early calculations of both the initial capital cost and the cost per kilowatt hour imply a favorable economic future for OTEC technology. Although the first units built will cost considerably more per kilowatt than fossil-fueled or nuclear powerplants, expected savings due to technological improvements, assembly line production, lower operating and maintenance costs, no fuel expense, and long life operation may allow OTEC powerplants to become economically competitive with more conventional energy sources by the 1990's.

Early estimates of the capital cost of an OTEC powerplant varied widely, since the different OTEC proponents assumed different temperature differentials, different design parameters, and different materials for the working fluid and heat exchangers. J. Hilbert Anderson was the first Amercian to publish an OTEC design and cost estimate; in 1965, he calculated that a 100 MW plant would cost on the order of $165/kW.[18/] Even if the effect of inflation is added, that figure is generally considered too low. More recent estimates by the several OTEC proponents are listed in Table III-1.

Even though these estimates are all in 1974-1975 dollars, they vary because of the different assumptions mentioned above. Furthermore, the University of Massachusetts, CMU, and APL all assumed that various aspects of OTEC technology could be developed or improved with a minimum of research. Consequently, their figures generally reflect the capital cost of an OTEC plant after a period of research and development. TRW and Lockheed, on the other hand, were constrained in their analysis to state-of-the-art technology and costs. Their figures represent the capital cost of an OTEC plant if it were designed and built today.

CMU researchers have studied the capital cost figures listed in the table and have recalculated them assuming identical temperature differentials and cost per square foot for heat exchangers. That comparison is also listed in Table III-1. With identical assumptions, the capital costs projected by the various OTEC researchers fall within a reasonably narrow range of $1,540-$1,995/kW.

OTEC capital costs projected through the year 2020 are listed in Table III-2. Assuming the first units will be built with present technology, the cost range for 1985 reflects the present difference between TRW and Lockheed figures, due mainly to different working temperature differentials.

TABLE III-1

CAPITAL COST COMPARISON

	CAPITAL COST/ EXCLUDING OPERATING COST, WITH SIMILAR HEAT TRANSFER CO-EFFICIENTS	CAPITAL COST/ EXCLUDING OPERATING COST, WITH SIMILAR HEAT TRANSFER COEFFICIENT, TEMPERATURE DIFFERENTIAL, AND HEAT EXCHANGER COST PER FOOT
CMU	$1,187	$1,995
U. MASS	712	NO DATA
APL	357	1,540
TRW	1,812	1,654
LOCKHEED	2,594	1,901

Source: Progress Report: Solar Sea Power Project[17/]

TABLE III-2
OTEC COST DATA

YEAR	CAPITAL COST* ($/kW)	OPERATING COST (mills/kWh)	LABOR REQUIREMENTS		USER COST $/ENERGY UNIT (mills/kWh)
			OPERATION (MAN MONTHS/YR)	CONSTRUCTION (TOTAL MAN MONTHS)	
1975	N/A	N/A	N/A	N/A	N/A
1985	2100 – 2600	1.7	32 – 35 MAN CREW	$7 - 10 \times 10^4$	42 – 51
1990	1400 – 1900	1.7	32 – 35 MAN CREW	$7 - 10 \times 10^4$	29 – 38
2000	1000 – 1500	1.7	32 – 35 MAN CREW	$7 - 10 \times 10^4$	21 – 31
2020	700 – 1200	1.7	32 – 35 MAN CREW	$7 - 10 \times 10^4$	15 – 25

ASSUMPTIONS AND DATA SOURCES

- 0.9 PLANT USE FACTOR
- 0.15 FIXED CHARGES RATE
- USER COST $= \dfrac{CC(.15) + OM}{(.9)\,(8.76)}$
- CAPITAL COST RANGE EFFECTED BY OCEAN SITES WITH $19^\circ C < T < 22^\circ C$
- EFFLUENT WATER WILL NOT INTERFERE WITH PLANT OPERATION
- NO TRANSMISSION COSTS INCLUDED
- SITES NEAR ENOUGH TO CONSUMERS SO TRANSMISSION WILL BE ECONOMICALLY FEASIBLE

* THIS CAPITAL COST FORECAST ASSUMES THAT COST REDUCTIONS EFFECTED BY TECHNILOGICAL ADVANCES WILL OCCUR SEPARATE FROM AND AFTER REDUCTIONS AFFECTED BY THE MASS PRODUCTION OF POWER MODULES. HOWEVER, SINCE SIGNIFICANTLY IMPROVED HEAT EXCHANGERS COULD BE DEVELOPED MUCH MORE QUICKLY, CAPITAL COSTS COULD BE REDUCED MUCH MORE QUICKLY.

Source: EEA, Inc.

The projected savings in capital costs attributable to both improved technology and large scale implementation are reflected in Table IV-2 as the range of estimated costs in 2020. However, since OTEC technology most likely will improve at the same time as mass production reduces costs, the capital cost levels projected for 2020 in fact could be reached earlier.

Like most solar technologies, OTEC is capital-intensive; larger amounts of capital will be needed to construct an OTEC plant than are presently needed for a similarly sized conventional power plant. However, since OTEC power is derived in a low temperature-low pressure environment, OTEC plant components may last much longer than those of conventional plants. Heat exchangers made of titanium may have a useful life of 35 years; the hull itself could conceivably last a century. Consequently, user cost in mills/kWh may more accurately indicate the relative cost of OTEC power.

C. Material Requirements

Without a working prototype or a demonstration model, it is difficult to accurately predict the material needs of an OTEC plant. In general, however, neither material nor construction facility needs should strain current or projected industry capabilities. Depending on final design configurations, the hull and cold water pipe will most likely be constructed of some combination of steel, reinforced concrete, or fiberglass. Fabrication of components will probably take place in shipbuilding yards using many of the same techniques as in the construction of deep sea oil drilling rigs, while final assembly will probably occur at protected deep-water sites.

The construction of heat exchangers could necessitate the expansion of the current titanium industry, if titanium were chosen as the heat exchanger material. If ERDA's latest projection of OTEC power availability in the year 2000 (20,000 MW) 6/ were to be fulfilled using titanium heat exchangers at the present projected usage rate (3700 tons/100 MW), OTEC heat exchangers would consume approximately 40 years of current U.S. titanium production capacity.

The only other potentially limited resource needed for OTEC plants is the working fluid. If ammonia were chosen, each 100 MW OTEC plant would need approximately 3×10^6 pounds. Since this inventory would not have to be replenished (except in case of a leak), and since ammonia may eventually be produced at sea using OTEC electricity, the deployment of OTEC plants should not strain ammonia supplies.

An OTEC plant uses no "fuel"; therefore, fuel cost and availability will not constrain OTEC development. A constructed OTEC plant needs only an adequate temperature differential to produce electricity, and a virtually limitless supply of sufficiently warm ocean surface water lies within 20° of the equator.

D. Comparison and Displacement of Alternative Energy Sources

Ocean thermal energy conversion systems are unique among the solar technologies in the sense that their operation will not be interrupted when the sun does not shine. Solar energy is continually converted and stored in the form of warm ocean surface waters. Except for slight diurnal and seasonal variations, the temperature of these waters remains fairly constant. Consequently, OTEC plants will be able to operate 24 hours a day, year-round, without the added expense of either energy storage systems or conventionally fueled back-up power systems.

OTEC plants are therefore the only solar technology capable of generating base-load electricity without large-scale storage capacities. Since OTEC plants have the potential to produce base-load electricity for existing grids, they are capable of displacing fossil-fueled and nuclear powerplants, the two most common base-load electricity generators.

Furthermore, OTEC plants may be used to produce energy intensive materials, thus displacing and saving the more conventional fuels currently used in that production. For instance, OTEC plants may displace the conventional fuels used to produce aluminum from bauxite. If hydrogen became a significant energy source in the future, the production of liquid hydrogen by an OTEC plant would help conserve supplies of the more conventional fuels liquid hydrogen would replace. The production of ammonia at sea would displace the natural gas and liquid hydrocarbons used in the ammonia producing processes. Finally, OTEC systems may be used to produce synthetic fuels (e.g., liquid natural gas), if some source of carbon can be economically shipped to OTEC sites. The economic problems of raw materials transportation may be lessened, however, by siting OTEC plants either near the raw material source and/or near the potential markets.

If OTEC power transmission constraints or price structures promote increased marine traffic or industrial development, secondary impacts may occur. Such impacts might arise both from physical alterations of the environment during facility construction and operation and from related changes in area land use, population, and economy. Development in the coastal zones would be regulated by State and local land use regulations and by related plans or procedures under the Coastal Zone Management Act. Development of water-based industrial facilities, if it occurred, would raise further questions concerning potential impacts and appropriate jurisdictional controls.

SECTION IV

ENVIRONMENTAL IMPACTS

A. Introduction

Since OTEC plants will operate in an ocean environment, their effects on ocean ecosystems, climate, and biosystems will be the major environmental concerns. However, the secondary effects of construction of OTEC plant components and their transportation to operating sites will also need to be studied. Finally, the development of OTEC technology may impact local institutions (e.g. coastal construction communities) and, more important, international relations. Since the ocean is one of man's greatest resources, its increased utilization will become a matter of growing concern for all nations.

B. Potentially Toxic Effects of Metallic Elements

Current baseline designs project the need for approximately 100 ft^2 of heat exchange surface area for each kW of power produced by an OTEC plant. Therefore, a 100 MW plant would maintain on the the order of 10 million square feet of heat exchange area, all of which would be continually subjected to the erosive and corrosive forces of sea water flow, causing a certain quantity of metallic elements to be dispersed into the ambient sea water every day. (Although the optimum size of an OTEC plant has yet to be established, 100 MW has been generally accepted for baseline designs.) The quantity of exchanger material loss will not only limit the useful life of the heat exchanger, but it will also partially determine the plant's environmental impact on ambient sea water.

The U.S. Environmental Protection Agency (EPA) has established upper limits for trace element concentrations in marine waters based on recommendations from the National Academy of Sciences. According to the EPA: "The acceptable limits specified in the criteria for substances which exhibit toxic effects were derived by the application of scientific judgment to lethal dose or lethal concentration data in a manner that provides a margin of safety to test organisms."[19/] By determining the rate of exchanger surface loss in normal flows of sea water, it should be possible to approximate whether trace element concentrations in that flow exceed EPA limits. The types of marine life indigenous to potential OTEC sites and therefore susceptible to metallic toxicity could be determined by searching the appropriate literature.

Copper/Nickel

OTEC researchers project that if 90/10 copper-nickel is used in the heat exchangers, sea water forces could cause an exchanger wall thickness loss of approximately 1-4 mils per year.[10/11/] Assuming the worst case, the entire surface area losing four mils of material/year, 3333 ft^3 of the alloy would be eroded/corroded out of a 100 MW plant each year, or approximately 9 ft^3 per day. Assuming the same density for copper and nickel, 555 lb/ft^3 (8.9 gm/cm^3), and assuming a sea water flow of 2×10^9 ft^3 (57×10^9 liters) per day, the sea water flow at plant outfall would contain a copper-nickel concentration of 0.04 mg/l, only slightly below the EPA limits of 0.05 mg/l of copper and 0.1 mg/l of nickel. However, in actual practice, the sea water flow may be as much as twice as large and research to improve the coefficient of heat transfer may allow considerably smaller heat exchanger areas. Under any conditions the metallic concentrations would be quickly diluted beyond the plant outfall.

Yet copper-nickel heat exchangers would seem to pose more potential environmental problems than any other material candidate. Two species of West Coast mollusks exposed to 0.1 mg/l of copper showed 100 percent mortality within 72 hours. Mussels showed 100 percent mortality at 0.14 mg/l of copper within 24 hours. Copper in low concentrations is also toxic to oysters. Fifty percent of copepods and tubeworms exposed to copper doses of 0.5 mg/l died within 13 and 2 hours respectively. Furthermore, 0.1 mg/l of copper inhibited photosynthesis of giant kelp by 70 percent within 48 hours.

Finally, the effects of copper may be even more serious because it may be concentrated by marine organisms, allowing it to be available in higher concentrations in the food chain. Concentration factors of marine organisms are 30,000 in phytoplankton, 5,000 in soft tissues of mullusks, and 1,000 in fish muscle.[19/]

Aluminum

The use of aluminum in the heat exchanger would appear to be of less environmental concern, even though the aluminum would probably erode/corrode at a higher rate than the copper/nickel alloy. Assuming the same total exchanger area, 10 million ft^2, and a yearly erosion/corrosion rate of 6 mils,[9/] 13.7 ft^3 of aluminum would be dispersed each day in the sea water flow. At a density of 168 lbs/ft^3 (2.7 gm/cm^3), 2300 lbs (1.04×10^9 mg) of aluminum would be washed out of the heat exchanger each day by 2×10^9 ft^3 (57×10^9 liters) of water, a continual concentration of 0.018 mg/l. This is approximately 1 percent of the EPA limit for aluminum concentrations in sea water (1.5 mg/l). However, little is known of the toxic effects of aluminum on specific marine organisms.

Titanium

EPA has established no limits for the concentration of titanium in sea water and little or no testing has been done on the effects of titanium on marine life. However, the use of titanium in the heat exchangers would probably allow for lower overall surface areas, and the rates of erosion/corrosion for titanium in sea water are known to be very low, probably much less than one mil/yr.[9/] In fact, Lockheed expects a 20-mil thick titanium wall to have a useful life of 35 years.[10/] Although little is known of the effects of titanium on marine life, its outfall concentrations would almost certainly be lower than the concentrations of either copper-nickel or aluminum for similarly sized plants.

Plastic

If stress and cracking problems can be overcome, and if thermal transfer properties are adequate, heat exchangers may be constructed out of plastic, especially since the use of plastic may significantly lower the capital costs of OTEC plants. If plastic heat exchangers were used, the problem of toxicity due to heat exchanger erosion/corrosion would be obviated.

C. Potential Ecological Impacts of Ocean Water Mixing

An OTEC plant will continually pump to its condensers near the ocean surface vast quantities of cold deep ocean water; it will pump a similar amount of warm surface water through its evaporators. This artificial mixing of natural thermoclines, salinity gradients, and biotic species near an OTEC plant could have an adverse affect on local marine ecosystems. For instance, temperature is the single most important environmental variable affecting marine organisms,[19/] and operating OTEC plants by their nature modify somewhat the natural thermoclines in their vicinity, lowering surface temperatures slightly and perhaps raising temperatures slightly at the level of condenser outfall. The extent to which ambient surface water temperatures are lowered and natural thermoclines disrupted will depend on plant design and site conditions. However, changes caused by a 100-240 MW OTEC plant should be minimal, since immediately at plant outfall surface and deep water temperatures will be changed only the order of 1-3°C.[20/] Furthermore, computer modeling studies are currently underway to determine plant outfall levels and patterns which would minimize this thermal disturbance.[21/22/]

The specific effects on marine life of thermal changes of the magnitude expected to be caused by OTEC operation have not been well defined. First of all, the thermal change effected by an OTEC plant will be considerably lower than that effected by more conventional power plants. (A nuclear power plant, for instance, will discharge cooling water at 16°F above intake temperatures.[23/]) Secondly, almost all research relating to thermal stress on marine species has studied the effects of thermal increases, while an OTEC plant's only certain thermal impact will be to decrease surface water temperatures. (OTEC plants may be designed so that condenser water is pumped out at levels where its temperature is similar to that of ambient water.) Research is needed on the effects of slight thermal decreases on marine species indigenous to potential OTEC sites.

For marine organisms small enough to pass through the heat exchangers themselves, however, the temperature changes may be more serious than for organisms in the ambient water, since they will be subjected to the temperature changes in a short period of time. Depending upon the design of the evaporators and the sea water flow rates, marine organisms carried through the evaporators will experience a 1-3°C drop in approximately 10 seconds. The effects of such a rate of change would have to be determined for specific organisms indigenous to specific OTEC sites.

Besides the temperature changes, any forms of marine life entrained in the deep ocean water pumped up to the surface will also be subjected to changes in pressure, salinity gradients, and levels of turbidity and dissolved oxygen. All these factors affect the natural balance of marine ecosystems, and all will be disturbed due to the artificial upwelling of deep ocean water. The specific effects on specific marine species can be studied both through literature searches and laboratory testing.

Finally, marine biota may be affected by impingement on the screens covering the cold and warm water intakes. The environmental problem of impingement has also been studied in relation to floating nuclear powerplants,[23/] and the effects during OTEC operation should be similar. For marine biota, impingement is expected to be confined predominantly to small fish and pelagic invertebrates. Small schooling "bait" fish, jellyfish, and pelagic crustaceans are likely to be impinged in the greatest numbers. The potential for ecologically or commercially significant losses is small.

D. Potentially Toxic Effects of Working Fluid Leaks

Since in each OTEC plant millions of square feet of heat exchange surface area only 20-40 mils thick will be exposed to constant physical and chemical stress, there is a strong possibility leaks may develop in the working fluid transport system. When the water pressure is greater than working fluid pressure at any point in the working fluid loop, a leak would result in seepage of sea water into the working fluid, in sufficient quantity causing serious cycle efficiency losses. When, on the other hand, the working fluid pressure exceeds the water pressure at a leakage point, the working fluid would seep into the sea. Leaks in either direction could cause potential environmental problems, and both could happen in a single system at the same time.

Although ammonia is not the only working fluid candidate, it seems most likely to be chosen because of its excellent thermal properties. Therefore, the potentially toxic effects of ammonia leaks into ambient sea water are presented here.

If pressure differentials allow the inward leakage of sea water, a water cleanup system would have to be installed in the working fluid loop. Such a cleanup system could take several forms, the most likely being a distillation column. According to Lockheed's OTEC feasibility study, a distillation cleanup system for a 160 MW net power plant would dump a maximum of 65 gallons of water into the ocean every hour.[10/] This effluent water, cooled down before dispersal to 100^{o}F, would have an ammonia content of approximately 3 percent. In such small amounts, neither the heat nor the ammonia dispersed into the ocean from a distillation-type water cleanup system would have a significant effect on the environment.

Since a working fluid inventory monitoring device would be installed in OTEC plants to give early warning of ammonia leakage into the sea water, under normal operating conditions ammonia losses into sea water would fall within tolerable limits. Sea water flow through a baseline 100 MW OTEC plant has been calculated to be on the order of 2.4-4.8 x 10^9 ft^3/day. Assuming a minimum volume of 2 x 10^9 ft^3 (57 x 10^9 liters) per day, ammonia would have to leak into the sea water at a rate of 5 x 10^4 lbs (23 x 10^9 mg) per day to reach the U.S. EPA's limit for ammonia concentration in marine water (0.4 mg/l).

Since the normal operating inventory of ammonia for a 100 MW OTEC plant has been calculated to be on the order of 2-3.5 x 10^6 lbs, even at the upper limit the EPA water quality standard would not be exceeded unless the plant were losing more than 1 percent of its total inventory each day. Such a serious malfunction could only result from a major breakdown, a collision with an ocean-going vessel, or a tropical storm.

However, a natural or manmade disaster could cause an ammonia spill which would pollute marine water beyond EPA standards. The depth of the layer into which the leaked ammonia would mix and the volume of ocean water impacted can only be determined after final decisions on design parameters and <u>in situ</u> testing of currents and thermoclines are made.

Little information is available on the toxic effects of ammonia on specific marine organisms. However, because of the slightly higher alkalinity of sea water, ammonia may be more toxic in sea water than in freshwater.[19/]

E. Potential Ecological Impacts of Biocides

Chlorine has been suggested for use as a biocide to prevent biofouling on the sea water side of heat exchange surfaces. OTEC proponents have suggested an application rate of 0.1-0.5 ppm. The U.S. EPA's Proposed Criteria for Water Quality states that concentrations of free residual chlorine in marine waters in excess of 0.01 mg/l are unacceptable. Although proposed initial concentrations in an OTEC plant are 10-50 times greater than EPA's acceptable limit for marine water, those concentrations would be diluted quickly by ambient sea water beyond the outfall of an OTEC plant. The rate of dilution could be determined by dispersion modeling.

Laboratory studies would also have to determine which marine species would be affected and to what degree by the chlorine discharge. Furthermore, chlorine mixed with ammonia may be even more toxic.[19/] Since the possibility of such a mixture exists in an OTEC plant where ammonia is used as the working fluid and chlorine as a biocide, studies should be made to determine the potential environmental effects of possible mixtures.

In general, marine fish have shown a slight irritant activity when exposed to chlorine concentrations of 1 mg/l and a violent irritant activity at 10 mg/l. Since chlorine will be added to flow-through sea water at a rate only 0.5-0.01 percent of the rate needed to cause slight irritant activity, the toxic effects of the chlorine on marine fish should be minimal, especially considering the chlorinated water will be quickly diluted by ambient sea water.

Oysters, on the other hand, reduce pumping activity when exposed to chlorine concentrations of 0.01-0.05 mg/l and could not maintain effective pumping in chlorine concentrations of 1.0 mg/l. Samplings taken at potential OTEC sites would help indicate whether marine organisms which could be harmed by chlorine discharges were present.

The potentially toxic effects of chlorine use as a biocide may be obviated, however, by the use of mechanical cleaning devices. For example, the sea water side of the tube in a shell-and-tube exchanger could be brush-cleaned, although the individual component being cleaned might have to be decommissioned temporarily. An automatic in-operation mechanical cleaning system involving the passage of a rubber ball every 5-10 minutes through each exchanger tube is also being considered.

The heat exchanger surfaces might also be chemically coated with a toxic substance to minimize biofouling. Salts of copper, mercury, arsenic, tin and antimony are currently used as biocides in marine coatings; however, the environmental consequences of such toxicants would have to be studied.

Anti-biofouling fluorochemicals are currently being applied to metal surfaces and tested in marine environments, and research is being done on the possibility of manipulating the initial exchanger surface properties to control microbiological slime formation. Finally, a plastic coating may be applied to exchanger surfaces to inhibit biofouling if heat transfer problems can be overcome.[9/]

F. Potential Worker Safety Problems

The use of different chemicals in OTEC plants (e.g., ammonia or propane as a working fluid, chlorine as a biocide) could endanger the safety of construction, operation, or maintenance personnel. Therefore, safety guidelines similar to those already in effect in industry for handling those chemicals will have to be established.

The possibility of fires or explosions would be especially serious if propane were chosen as a working fluid, which seems unlikely at the present time. Propane would tend to vaporize in seawater; if undetected, it might collect underwater, posing the possibility of an underwater explosion.

The Occupational Safety and Health Administration has set standards limiting the concentration of various toxic materials to which an employee may be exposed. The maximum allowable concentration of chlorine (8-hour weighted average) is 1.0 part per million (ppm).

Ammonia is less flammable than propane, but its use still may lead to fires, explosions, or noxious gases. The gas produces slight irritation of the eyes and throat at concentrations of 280 to 490 mg/m^3. Higher concentrations of 1700 to 4500 mg/m^3 are required to induce pulmonary edema. Yet ammonia is not considered to constitute a serious threat to human health as an air pollutant.[24/] The OSHA has limited the maximum allowable concentration of ammonia (8-hour weighted average) to 50 ppm.

However, ammonia's strong odor below toxic levels would allow leaks into the air to be readily detected. Furthermore, inventory monitoring devices would warn OTEC operators of significant working fluid leaks, allowing repairs to be made quickly.

G. Potential Climatological Impacts of Lowered Sea Surface Temperatures

The operation of an OTEC plant may slightly lower the temperature of ambient ocean surface water. A slightly lower ocean surface temperature would lead to slightly lower air temperatures at the local air-water interface. Such temperature anomalies may affect other aspects of the microclimate, e.g., winds and currents.

For a single 100 MW OTEC plant impacting only 10-40 square kilometers of ocean surface, the microclimatic effects would probably be insignificant. For a 100 MW plant operating in the summer, 11 square kilometers of ocean surface may be lowered a maximum of 0.32°C; for a 240 MW plant, 42 square kilometers of ocean surface may be lowered at maximum of 0.54°C.[20/] Moreover, the ocean surface exhibits a natural ability to return to an equilibrium temperature. Lower surface temperatures will increase heat flow back into the oceans 60-70 $cal/cm^2/day/°C$)[22/] because of decreased back radiation and lower evaporation losses, thereby partially offsetting heat losses due to the power system.

Several OTEC plants operating in the same general ocean area may impact the local climate more seriously. However, OTEC plants could not be placed too closely together, because they might lower surface temperatures enough to interfere with the temperature differentials needed for efficient operation. Consequently, lowered surface temperatures would probably disturb OTEC operations before they would disturb the local climate.

H. Social and Institutional Impacts

Although OTEC is a new, energy producing technology, its development should have little impact on social or institutional structures beyond that typically associated with large-scale construction projects. Thousands of new jobs may be created, but fabrication sites and techniques are already available in coastal ship-building communities, especially those equipped to build large deep-sea oil drilling platforms. However, deep-water protected areas near deployment sites likely will be required for final assembly, causing transportation and support problems typical for any deep-water construction project.

Since OTEC plants take advantage of the natural energy conversion and storage capabilities of the ocean, some may be built to operate as base-load electricity producing units, contributing their power to existing grids. Consequently, they will have little unique impact on utilities. A potential problem may develop, however, with regard to jurisdiction over OTEC plants operating off the coast and the pricing structure of electricity sold to a national grid.

The most serious institutional problem posed by the operation of OTEC plants will be the question of international rights and responsibilities. The growing recognition that the ocean may be one of man's last untapped resources is already leading to international discussion, litigation, and, in some cases, friction over the rights to utilize these resources. International legislation will have to be written to allow for the installation and maintenance of OTEC plants in international waters. The problem of possible international royalties will have to be solved. International arbitration will be needed to resolve questions of responsibility and liability. In short, OTEC could open up a new area of international concern about the ownership and operation of energy-producing installations in international waters.

SECTION V

NEPA DOCUMENT WORK PLAN AND ENVIRONMENTAL RESEARCH PROJECTS

A. Introduction

The purpose of this section is to lay out a preliminary draft work plan for environmental analysis of the ocean thermal energy conversion technology being developed by the Energy Research and Development Administration (ERDA). It addresses the preparation of Environmental Development Plans, Environmental Impact Assessments, and Environmental Impact Statements, as well as the conduct of basic and applied research supportive of developing a better understanding of the environmental consequences of OTEC.

The work scheduled in this report should not be construed as official plans of either the Division of Solar Energy or of ERDA as a whole. The work shown is that identified by the contractor. Many of the projects identified and outlined in Section D can be carried out outside of ERDA and can be handled in a variety of ways. The scheduled work does not take into account breakthroughs or findings which may allow for significant reductions or expansions in effort, and it may not reflect specific work already underway in the public or private sectors.

B. Description of NEPA Documents

1. Background

The National Environmental Policy Act of 1969 (NEPA), implemented by Executive Order on March 5, 1970, and the guidelines of the Council on Environmental Quality of August 1, 1973, require that all agencies of the Federal government prepare detailed environmental statements on major Federal actions significantly affecting the quality of the human environment. The objective of NEPA is to build into the Federal agency decision-making process, at the earliest possible point, an appropriate and careful consideration of all environmental aspects of a proposed action in order that adverse environmental effects may be avoided or minimized.

In carrying out this mandate, each agency of the government has set out policy and procedures for implementing these requirements. ERDA currently operates under official guidelines originally established by and for the now defunct Atomic Energy Commission. In an effort to up-date and reorient the guidelines to ERDA's needs, alternative guidelines are now being prepared within ERDA.

Although the proposed revisions have yet to be finalized or adopted, because the proposed changes are so extensive and because this document is to serve as an input to a future agency planning effort, for purposes of this analysis the most recent proposed revision (November 1, 1976) has been used to represent the future official guidelines. The discussion of NEPA report requirements and the recommended work schedule is predicated on the guidance provided in the November 1 draft revision.

The backbone of ERDA's compliance program is the preparation and review (by the agency and the public) of documents addressing the environmental aspects of programs and projects of the agency. Three types of documents are particularly important: Environmental Development Plans (EDP's), Environmental Impact Assessments (EIA's), and Environmental Impact Statements (EIS's). Each is described below.

2. Environmental Development Plans

An Environmental Development Plan (EDP) is the basic ERDA management document for the planning, budgeting, managing, and reviewing of the broad environmental implications of each energy technology alternative for each major ERDA research, development, and demonstration and commercialization program. The EDP is designed to identify environmental issues, problems, and concerns as early as possible during the program's development, to analyze the available data and assess the current state of knowledge related to each issue, problem, and concern, to set forth strategies to resolve these, to set forth the processes by which the public is involved in identification and resolution of these issues, problems, and concerns, and to designate significant milestones for resolution of these issues, problems, and concerns. The timing of the EDP's milestones reflects the sequencing of the technology development. EDP's, once completed, are made available to the public.

3. Environmental Impact Assessments

An Environmental Impact Assessment (EIA) is a written report, prepared by an Assistant Administrator or an ERDA program office, which evaluates the environmental impacts of proposed ERDA actions to assure that environmental values are considered at the earliest meaningful point in the decision-making process and which, based upon the evaluation, determines whether or not an environmental impact statement should be prepared. The EIA is intended to be a brief, factual, and objective document describing the proposed action, the environment which may be impacted, the potential environmental impacts during construction, operation, and site restoration, potential conflicts with Federal, State, regional, or local plans, and the environmental implications of alternatives.

4. Environmental Impact Statements

An Environmental Impact Statement (EIS) is a document prepared at the earliest meaningful point in the decision-making process, which analyzes the anticipated environmental impacts of proposed

ERDA actions and of reasonably available alternatives and which reflects responsible public and governmental views and concerns. An EIS is prepared in response to plans in the program's EDP or after the review of an EIA which identifies potentially significant impacts. The EIS goes through a specific preparation process involving agency and public review.

The EIS goes through four steps during its preparation. The preliminary draft is reviewed within ERDA, the draft is distributed the public for review and comment, the preliminary final incorporating comments submitted to ERDA in response to the draft is reviewed within ERDA, and the final EIS is issued reflecting the agency's final review and deliberations. This final EIS is then officially filed with the Council on Environmental Quality and distributed to the public. Except in special cases, no ERDA action subject to EIS preparation can be taken sooner than 30 days after the final EIS has been issued.

An EIS can be prepared covering programs, projects, or the use of ERDA facilities. In each case the document must reflect the utilization of a systematic interdisciplinary approach which will insure the integrated use of the natural and social sciences and the environmental design arts.

Contents of the report cover a description of the proposed action and alternatives, a description of the existing environment, an analysis of environmental impacts of the proposed action and its alternatives, and a specific review of the unavoidable adverse effects, resource use, land use implications, and the environmental tradeoffs represented by the pr   sed action and the alternatives.

C. NEPA Document Work Plan

Figure V-1 presents an environmental work schedule for various OTEC projects. Also included is a schedule for the various research projects which are proposed below.

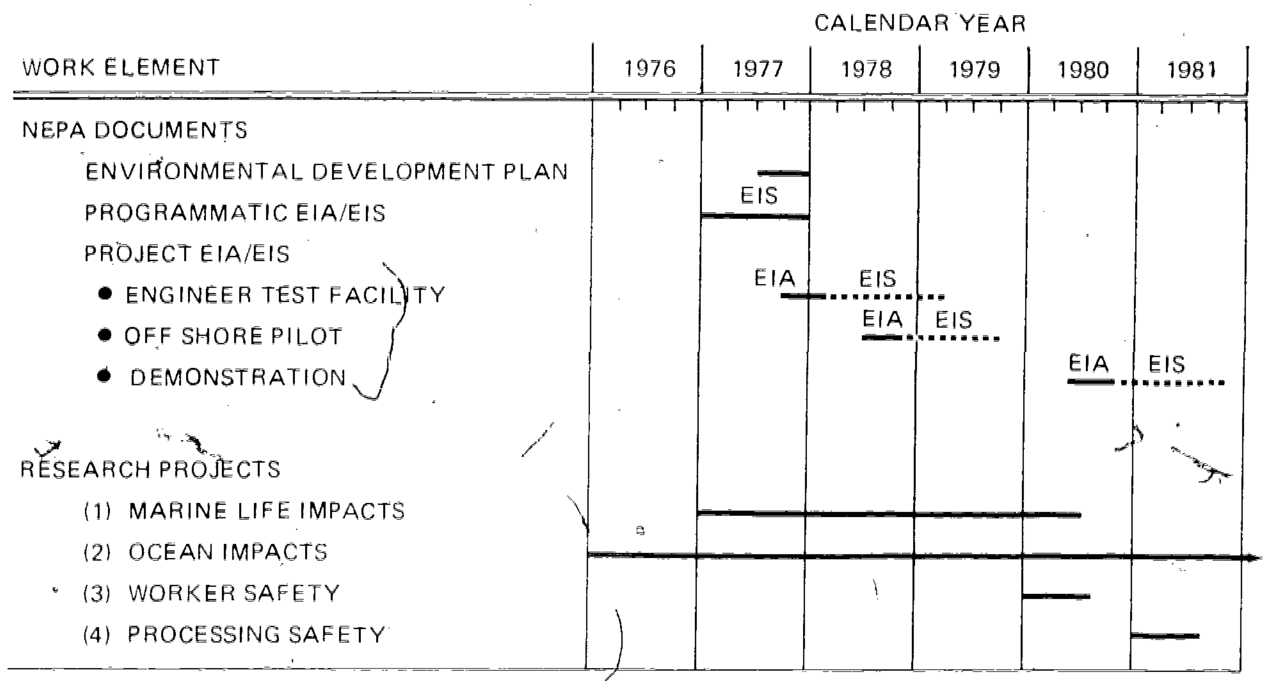
D. Research and Development Projects

Research is currently underway to study several of the environmental issues raised in this report. For instance, a combined CMU/University of Hawaii team is studying the potential effect of biofouling at a specific location off the coast of Hawaii; the Naval Research Laboratory and the Massachusetts Institute of Technology are using different kinds of computer modeling to study fluid dynamics and dispersion. Since OTEC technology is still in its early stages of development, it will be possible to adjust it to mitigate many of its environmental problems.

Through the preparation of EEA's environmental survey of ERDA's ocean thermal energy conversion program, other environmental issues were identified which could not be adequately analyzed within the context of this study due to the complexity of the problem, the general lack of necessary research data, and the level of effort and schedule of the EEA study. This section identifies specific follow-up research projects which the EEA staff felt were critical to the understanding of the environmental consequences of large scale commercial application of OTEC and which are not likely to be specifically or adequately addressed solely in the preparation of NEPA documents. Many other research projects were identified during EEA's study. This list represents a condensation and trimming down of draft lists to those projects which were felt to be of greatest importance to the advancement of OTEC use and the associated decision-making process within the Federal government.

FIGURE V-1

OCEAN THERMAL ENERGY (EA0304)
ENVIRONMENTAL WORK SCHEDULE



1. OTEC Marine Life Exposure Simulations

- Through laboratory or in situ exposure simulation, the effect of exposure to OTEC physical and chemical conditions on ocean flora and fauna will be analyzed.
- Specific species common to one or more OTEC candidate sites will be subjected to chemical and physical environmental changes simulating those anticipated during passage through heat exchangers or in passing through the outflow of the plant.
- The observed effects will be analyzed and extrapolated to estimate total impacts of OTEC commercial sized plant operation.

2. Analysis of OTEC Impacts on Ocean Environment

- Models to predict the impact of OTEC facilities on ocean temperature gradients and levels, nutrient distribution and depletion, water evaporation, solar energy absorption, and climate will be postulated and in situ monitoring data needs determined as may be required for model validation.
- An ambient monitoring program to take effect during pilot plant operation will be proposed and priorities established.
- Monitoring will be carried out at the prototype plant site.
- Data will be used to validate model parameters and relationships and the models applied to predicting possible impacts of large scale OTEC deployment.

3. Worker Safety Analysis

- For a prototypical OTEC facility, the number of workers, their duties and their locations at the facility should be determined.
- For each worker or type of worker, a work day schedule of duties will be developed and the potential for exposure to working fluid or biocide chemicals assessed. Quantitative estimates for the level and duration of exposure to each will be made and these exposures compared to available dose/effect information on the alternative subject materials. The analysis will cover startup, normal operation, and several failure modes.

- If significant hazards are identified, mitigating protective measures will be formulated and their cost estimated.

4. Safety of OTEC Based Processing

- The general safety considerations associated with the production of ammonia and hydrogen via OTEC energy production shall be identified and the safety record and procedures of conventional hydrogen and ammonia production investigated.

- Physical conditions at sea and operational differences of OTEC vs. conventional production operations for these materials will be examined and relative safety (associated control measures) of such facilities determined.

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