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DOE Ocean Energy Program - An Overview

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DOE'S OCEAN ENERGY PROGRAM - AN OVERVIEW

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ABSTRACT

This paper summarizes the background, current status and future plans, for the U. S. Department of Energy's Ocean Energy Program, which is directed toward making a significant contribution to National goals of energy independence. The paper will concentrate primarily upon Ocean Thermal Energy Conversion (OTEC), and will also address alternate technologies including wave and current energy and salinity gradients. Principal issues to be addressed include the status of technical development, critical technical issues, resource potentials, economic perspectives and legal/institutional issues affecting the commercialization of Ocean Energy. The DOE Ocean Engineering Plan will be summarized, with emphasis on the 1 MW test platform to be deployed in June 1980 and the Pilot Plant program to be initiated in 1980.

INTRODUCTION

In response to the increasing shortages of nonrenewable energy sources, there has been a growing worldwide interest in alternative energy sources with the emphasis on those which are renewable. The world's oceans represent a vast resource of renewable energy consisting of energy derived from solar radiation, gravity, and chemical compositions. The U. S. Department of Energy, responding to the National Energy Act, has developed and is now implementing an Ocean Energy Program directed at reducing the U.S. dependence on oil imports and other exhaustible fuels.

The focus of this program involves four ocean energy technologies:

- Ocean Thermal Energy Conversion (OTEC) which uses the temperature difference between warm surface water and cold deep water to produce electricity.
- Ocean Wave Energy Conversion which converts the mechanical energy of waves into a useful form of energy such as electricity.
- Ocean Current Energy Conversion which converts the kinetic energy of the ocean currents into electricity.
- Salinity Gradient Energy Conversion which uses the potential between two liquids of differing salinity to generate electricity.

A three-step strategy in the development and implementation of the program is being used:

- Identify the available ocean energy resources.
- Assure technical feasibility and cost effectiveness of potential energy extraction and conversion techniques.
- Develop technology to induce industry participation leading to commercial use.

The Ocean Systems Program funding is presently 95 percent OTEC, due to its greater near-term potential, with 5 percent directed toward alternative energy sources. Therefore, the primary focus of this paper will be on the OTEC program.

OCEAN THERMAL ENERGY CONVERSION (OTEC)

Concept Description. The OTEC concept uses the temperature difference between warm surface water (80°F) and cold deep water (40°F at 3,000 feet) to run a heat engine and to generate electricity. Figure 1 illustrates the basic closed or Rankine cycle of principal interest. Alternate cycles will be discussed later. In the closed cycle, a working fluid such as ammonia is used with an evaporator, a turbogenerator, a condenser and a pressurizer (feed pump). Warm surface water is pumped into the evaporator where subcooled ammonia liquid is turned into vapor. The exhaust of the turbine is wet ammonia vapor. The ammonia is condensed in a surface condenser which receives its cooling water through a deep cold-water pipe. The condensed ammonia is pressurized before it is again fed into the evaporator, completing the cycle. (1)*

* Number in parenthesis refer to References listed at the end of the paper.

A fundamental advantage of OTEC over other solar energy systems is the constant availability of the resource (day and night, all year). Although the basic thermal cycle is rather inefficient and requires very large heat exchangers and other hardware, the fuel source is both free and inexhausible. Another advantage is its potential for supplying large base load power requirements.

Resource Potential. The potential for energy generated from ocean thermal differentials is between 10^6 and 10^7 MW. The regions of greatest potential are those with the highest temperature differential between the surface and deep waters, located between 20° N and 20° S latitude, encompassing a circumferential belt accounting for about 20% of the ocean surface. Both coasts of Africa, the tropical west and southeastern coasts of the America's, and many Caribbean and Pacific islands are within this zone. The potential areas of OTEC deployment for the United States include (2):

- The Caribbean (Puerto Rico, Virgin Islands);
- The Hawaiian Islands;
- Gulf Stream waters off the southeastern coast;
- The Gulf of Mexico

The major elements of the OTEC system include the following, which form the basis for DOE's OTEC technology development program:

- The power system, including heat exchangers and turbo-generators
- The cold water pipe (CWP) which transports massive quantities of cold water from a depth of about 3000 feet
- The platform and its mooring system
- The transmission cable connecting the platform generators with the shore power grid.

The program also includes extensive environmental studies, including thermal resource assessment, environmental data required for design and assessment of effects on thermal distributions, marine life and other environmental considerations.

Heat Exchangers. The ability of the heat exchangers (H/X) to efficiently convert the working fluid from a liquid to gaseous state and vice versa with low temperature differentials is the key to an economically viable OTEC system. For this reason, the majority of OTEC funding has included an exhaustive series of laboratory and at-sea test to evaluate the following:

- Basic H/X concepts - shell and tube versus plate type heat transfer surfaces, with various forms of surface enhancement (fins, coatings, etc.), flow rates, temperatures and pressures.
- Biofouling countermeasures, including chlorination and various mechanical cleaning concepts, to reduce film build-up and corresponding loss of heat transfer efficiency.
- Cost-effectiveness and resistance to seawater degradation of alternate heat exchanger materials with emphasis on titanium and aluminum alloys.

Testing of heat exchanger components has been carried out at Argonne National Laboratories, the Navy's coastal testing facility in Panama City, Fl, and at various test facilities in Hawaii and the Virgin Islands to sample a cross-section of potential OTEC fouling environments. The next major step in the development of H/X is OTEC-1, a test program involving installation of 1 MW shell-and-tube heat exchangers and an ammonia working fluid system on a surplus T2 tanker. The conversion of the tanker will be completed in late May 1980, followed by deployment to Hawaii for a 9-month at-sea test. This will be followed by two 9-month tests of alternative components.

The current status of the critical H/X developmenta program is as follows:

- Adequate heat transfer efficiency can be developed with state-of-the-art concepts for economic viability at commercial scale (100-400 MW)
- H/X cleaning and biofouling countermeasures are effective at environmentally acceptable levels.
- Preliminary designs of shell and tube (Power System Development I) and plate type (Power System Development II) H/X up to 10 MW modular size have been completed.

Open Cycle OTEC. The open cycle OTEC power system or Claude cycle uses seawater as the working fluid. Warm seawater is deaerated and passed into a flash evaporation chamber, where a fraction of the seawater is converted into low pressure steam. The steam is passed through a turbine which extracts energy from it and then exits into a condenser. The condensate need not be returned to the evaporator as in the case of the closed cycle. Rather, if a surface concenser is used, the output is desalinated water. Or, if a spray, a direct-contact condenser is used, the condensate is mixed with the cooling water and discharged back into the ocean. The advantages of the open cycle includes:

- Reduced biofouling and corrosion problems
- Production of fresh water as a byproduct, which is a critical need in many tropical areas.
- No noxious or dangerous working fluid

The current DOE program for open cycle OTEC is in the early R&D stage where closed cycle OTEC was perhaps 5 years ago. Because of its less developed status, open cycle OTEC is considered a second generation concept to be demonstrated after the initial thrust toward closed cycle OTEC is completed.

Cold Water Pipe: The OTEC CWP is the most formidable ocean engineering challenge to be met in the realization of OTEC's potential. A 3000 foot long large diameter pipe (up to 100 feet for a 400 MW commercial OTEC plant) has no parallel in offshore or deep ocean construction, and represents a major advance in the state-of-the-art in design, construction and deployment of offshore structures.

Initial studies in the late 1970's (3) identified the criticality of the CWP, and led to DOE's development of a CWP validation program involving the following three elements:

- Development of both time and frequency domain computer simulations to predict CWP dynamic response to currents, platform-induced motions and hydrodynamic phenomena such as vortex shedding
- Model tests of specific platforms/CWP configurations in hurricane sea states to compare responses to analytical predictions and at-sea test results.
- At-sea tests of reduced-scale CWP's to provide response data in realistic operating environments.

The initial at-sea tests involved a 5 foot diameter steel CWP suspended below a tension-leg drilling platform off California, which represented a 1/6 scale simulation of the 30 foot diameter pipe anticipated for the 40 MW Pilot Plant to be discussed below. The corresponding model test and computer simulations completed in February 1980 indicate encouraging agreement. A 10 ft. diameter, 1000 foot long fiberglass CWP is to be tested at sea in 1981 to further validate design, construction and deployment procedures in advance of the Pilot Plant. Further studies of larger commercial plant CWP's are planned for FY 81 and beyond to complement recent preliminary designs of Pilot Plant CWP's (4) (5).

The current status of CWP development is as follows:

- Valid computer simulations and model test procedures are available to predict dynamic response.
- Vortex shedding is identified as a potential problem, though supression techniques are available
- Fiberglass, steel, lightweight concrete and elastomeric materials are viable for specific CWP applications
- A flexible CWP/platform connection is essential, and hinges are required along the length of steel and concrete pipes to reduce bending stresses

Platforms. DOE has evaluated the applicability of a number of platform geometries for large-size OTEC systems including ships (barges), spars, cylinders, spheres, submersibles and semi-submersibles of various sizes. Current DOE emphasis is on the ship or barge, which represents the state-of-the-art, and spars, which afford greatly reduced platform motions. Two 40 MW Pilot Plant reference baselines have been developed by DOE, a barge and spar, as shown in Figures 2 and 3, as well as a land-based alternative where the CWP follows the contour of the bottom to a depth of 3000 feet. The two floating options are intended to represent possible prototypes for larger commercial size OTEC platforms to be built in the 1990's.

One of the critical elements associated with the platform is the station keeping subsystem (SKSS), required to keep the system moored on site during even the most severe storms. The water depth and magnitude of mooring forces for ever the Pilot Plant are at the threshold of the state-of-the-art, while the commercial plant mooring requirements are well beyond it. For this reason, DOE instituted an SKSS development program in 1978 leading to preliminary designs of mooring systems for the spar and barge Pilot Plants (6)(7). Further studies directed at the commercial plant SKSS are programmed for FY 81 and beyond.

The current status of SKSS development is as follows:

- Analytical methods are available to predict response
- The current state-of-the-art can support the Pilot Plant program, but innovative concepts must be developed for the larger commercial plants.
- Data is needed on the fatigue characteristics of SKSS components,

particularly large diameter wire rope cables

Electrical Cable. The electrical cable connecting the platforms' generators to the shore grid is a high-risk element. Although submarine cables of equivalent voltage and power have been installed, none have been suspended from a moving platform. Thus, the portion extending from the platform to the bottom (the "riser" cable) will be subjected to cyclic loading never before encountered. The relatively low fatigue strength of the armored cables being considered places severe constraints on platform motions and cable bend radii. These limitations are particularly critical for small surface platforms such as the 40 MW barge Pilot Plant, which has relatively high motions. For larger platforms, the problem is correspondingly less. Figure 4 illustrates the riser concept being considered for the barge (8), with the cable being supported by a submerged buoy to reduce the length of the catenary. For the spar design, the problem is less severe since the cable can be rigidly attached to the CWP, which is anchored to the bottom. One concept which avoids the cable problem is the grazing OTEC plant which uses electricity generated onboard to power an energy-intensive manufacturing process such as ammonia or aluminum production.

The current status of the riser cable development program is as follows:

- The preferred cable concept involves high density polyethylene extruded around the conductor, wrapped with armoring cables, similar to state-of-the-art submarine cables. Design studies have been completed and component testing is underway.
- Cable motions remain a significant concern
- Underwater splices and other critical components such as hull/cable connections must be developed and demonstrated
- Conventional cable laying and trenching techniques appear applicable

Pilot Plant. The next major DOE ocean energy acquisition program following OTEC-1 will be the Pilot Plant, a complete OTEC system capable of producing as much as 40 MW net output, to demonstrate that the total OTEC closed cycle concept is technically and economically viable. The Pilot Plant will be built in the 1983-1985 timeframe, under a cost-shared agreement with DOE and private industry. The Program Opportunity Notice (PON) for the Pilot Plant is to be issued in the near future, with several teams being awarded parallel concept definition contracts. One or more of these teams will then proceed into preliminary design, and finally into Detail Design and Construction. As a minimum, one 40 MW Pilot Plant will be built, though recently Senate Resolution 1830 (9) was passed setting a goal of 200 MW of Pilot Plant capacity by 1985. If the corresponding house resolution passes and funding is provided for this expanded program, it is possible that up to five alternative Pilot Plant concepts will be carried to completion. It is anticipated that DOE will turn these plants over to the industrial consortia that cost-shared in their development once they have served their purpose to DOE.

In developing the Pilot Plant program, DOE has recognized that the initial stragegy should concentrate on tropical island markets (Puerto Rico, Hawaii, Virgin Islands, etc.) since they are entirely dependent on high-cost foreign fuel oil and are more subject to interdiction and embargo than the U.S. mainland. Also, their smaller baseload power requirements makes a 40 MW plant more attractive as a commercial entity than the U. S. mainland, where between 200 and 400 MW is normally considered as a minimum size commercial plant. Thus by deploying one or more 40 MW plants into the island markets in the mid 1980's, DOE will have accomplished its goal of demonstrating OTEC's potential.

Overall OTEC Program Schedule. Figure 5 illustrates the OTEC Ocean Energy program milestones and schedule corresponding to the foregoing discussion. Key elements include:

- Use of the OTEC-1 platform to test both PSD I and PSD II heat exchangers, providing valuable data on system performance and biofouling/corrosion control requirements
- Feedback from OTEC-1 and parallel developments of the CWP, cable and related environmental studies into the Pilot Plant procurement cycle.

Future OTEC Industrialization. Beyond the Pilot Plant, there is the obvious need to integrate OTEC into the U.S. Utility Market. Senate Resolution 1830 sets a goal of 10,000 MW of OTEC power by the year 2000, which forms the framework for DOE's planning for OTEC industrialization. DOE will not be directly involved in funding the ultimate commercialization of OTEC, or other ocean energy options, since this falls under the purvue of private industry rather than government. None the less, DOE is working toward this goal with a number of studies to identify markets, strategies and incentives leading to industrialization of OTEC. In particular, long-range studies are projecting potential energy costs for various markets, using the islands as a baseline. Figure 6 illustrates the anticipated OTEC energy cost for Puerto Rico versus oil-produced energy, indicating a significant potential within the next 10 years. The DOE studies are also identifying energy-intensive industries, such as aluminum and ammonia, where OTEC produced energy can gain an initial industrial acceptance in a dedicated mode. Finally, DOE is looking at various incentives such as tax write-offs, loan guarantees, subsidies and cost-sharing concepts to expedite the early industrialization of OTEC.

WAVE ENERGY

Concept Description - There are a large number of concepts which can extract energy from ocean waves, including the following, as illustrated in Figure 7:

- Heaving, pitching and/or rolling bodies which resonate with the waves to produce amplified motions which can be converted mechanically to electrical energy
- Cavity resonators, where passing waves excite an air column to produce rotation of an air turbine
- Focusing systems, which concentrate the wave energy in a relatively small region to amplify system response
- Pressure devices, where passing waves generate a differnetial pressure on a fixed mechanical system to excite a working fluid
- Various mechanical devices such as paddlewheels, flaps, rotating outriggers, belts, etc. either in the surf or offshore

Recent interest in wave energy conversion has centered in the programs developed in Japan, The United Kingdom, Norway, and the United States; and in a coordinated program by the participating memebers of the International Energy Agency (IEA), namely Japan, The United Kingdom, Ireland, Canada, and the United States. These programs will be discussed below.

Resource Potential. The ideal conditions for wave development are a strong shoreward wind, a long fetch and deep water. In the United States these conditions are met in the Pacific Northwest, Alaska, and to a lesser extent California, Hawaii and our island territories.

Wave power is variable. In the Pacific Northwest, significant wave power/crest length ranges from 5 MW/KM (megawatts/kilometer wave crest length) to 16 MW/KM with a yearly average of 12 MW/KM. For California this range is 3 MW/KM to 7.5 MW/KM with a yearly average of 5 MW/KM. For a relatively benign coast, such as along the Gulf of Mexico, values of less than 1 MW/KM are common. The total U. S. resource is an order of magnitude below OTEC, but of sufficient magnitude to warrant a continued DOE interest (10).

Concepts of Principal Interest Abroad. A number of promising systems are under investigation at the present time by several countries. The Japanese are working on development of a pneumatic resonating system and are presently testing a 1 MW barge configuration of this system, the "Kaimei", in the Sea of Japan. This test is being carried out in conjunction with the IEA and involves turbine designs by the Japanese, and the United Kingdom. The United States, Canada and Ireland are providing technical and financial support. Preliminary results are promising.

In addition to its involvement with the IEA, the United Kingdom has chosen four systems to examine both theoretically and experimentally. These are the Salter's Cam (a combination heaving and pitching system), the Cockerall Raft (a rotating outrigger), the Oscillating Water Column (a pneumatic device) and the Rectifier (a surging device). Additionally, they have conducted 1/10 scale at-sea model testing of the cams and rafts in Loch Ness and the Solent, respectively.

The Norwegians have centered their investigation on two systems. These are Fresnel focusing and point absorbers (a heaving system). At present they have conducted some initial tests on the Fresnel focusing devices in a model test facility outside of Oslo, Norway, and are in the planning phases for at-sea testing of the point absorbers.

DOE Wave Energy Program. The United States wave program is in a transition period from concept identification to system development. To date, DOE has sponsored a number of studies to aid in the identification of systems warranting further DOE consideration. Studies conducted so far include a wave resource study, participation in the IEA and support of small scale testing and theoretical assessments of selected systems.

In FY 1980, experiments will be conducted in wave tanks and comparative economic assessments will be made between alternative wave-focusing approaches. On the basis of these results, a pilot experiment will be planned and initiated in FY 1981.

OCEAN CURRENT ENERGY CONVERSION

Concept Description. Systems designed to extract the energy from ocean currents are similar to those for the extraction of energy from streams or the wind. Devices proposed include a number of types of propeller-driven turbines and devices which turn a drivewheel by the use of parachute type drogues, Figure 8.

Resource Potential. In the United States, there is only one area with a significant ocean current resource potential. This is the Florida Current off the southeast U.S. Early estimates of the extractable Florida Current resource suggested values between 10,000 and 25,000 MWe. DOE has suggested that the possible yield would range between 2,000 and 6,000 MWe considering mean seasonal current magnitude at the device operating depths (10).

Concepts of Interest. Presently, there are three current energy extraction systems which are being considered. These are:

- Axial Flow Converters - The current passes over the blades, which are oriented perpendicular to the drive shaft axis, creating thrust on the blades, causing them to rotate.
- Radial Flow Converters - In this configuration the blades are oriented parallel to the drive shaft.
- Linear Converters - Sail canopies attached to a driveable loop move with the force of the current. The loop is framed around a drivewheel which is operatively connected to an electrical generating subsystem.

DOE Ocean Current Program. As with waves, the DOE current program is in a transition between concept identification and system development. To date DOE has sponsored a preliminary resource assessment, a small test study of a linear converter, and an initial system engineering study and model test of a shrouded, rim-mounted axial converter.

In FY 1980, an engineering design of a prototype rotary turbine will be started, and system engineering studies of a full scale system will be conducted. Based on these efforts, it is anticipated that a pilot plant will be considered if the studies indicate potential economic viability.

SALINITY GRADIENT ENERGY CONVERSION

Concept Description. Salinity gradient energy conversion uses the energy potential that exists across a selective membrane between two solutions of different salinity. Two approaches for energy generation have been proposed. One utilizes the hydraulic pressure created by the flow of water between two water masses of varying salinity across a membrane (osmosis) to generate electricity. The second method is chemical and uses the electric potential between the two water masses to generate electricity.

Resource Potential. The total salinity gradient power from the runoff of fresh water to the oceans is roughly 10^6 MW (11). However, environmental considerations involving disposal of brine solutions have led to a closed cycle concept as being the most acceptable option. In such a system, a saline solution is recycled in a stratified pond. This concept can generate about 1 MW per 120 acres of land area, implying that it has application for local uses rather than as a source of baseload power.

Concepts of Interest. Presently there are two methods under study to utilize salinity gradient energy:

- Pressure retarded osmosis, or osmotic power, using the pressure difference derived from an osmotic pressure imbalance across a membrane separating salt and fresh solutions to drive a hydraulic turbine or water wheel.
- Reverse electrodialysis, or the dialytic battery, using the electric potential produced by combinations of selective membranes that permit one type of dissolved salt ion to pass through the membrane in one direction and the other in the opposite direction.

DOE Salinity Gradients Program. The DOE salinity-gradient program consists of basic and applied research and technology development to identify available ocean energy resources, identify potential energy extraction techniques, assess technical and economic feasibility, and to develop the technology to induce industry participation leading to commercial use. In FY 1979 dialytic battery experiments with a stratified solar pond were conducted, Phase I of a preliminary design of a 50 KW osmotic power unit was completed, along with cost analysis for a 20 MW dialytic power unit. Preliminary results on the available and extractable resource as well as projected costs indicate salinity gradients are not as economically useful at the ocean thermal options. Based upon this, salinity gradient funds were eliminated in FY 1980 and outyears to allow higher priority efforts to have a higher level of funding. If future studies reverse preliminary findings, then potential osmotic and dialytic sites will be identified, membrane and membrame module development and tests will be initiated.

SUMMARY

The DOE ocean energy program directs most of its FY 80 budget toward OTEC, and in particular, the OTEC-1 test platform procurement. In FY 81 - 83, OTEC will continue to be emphasized, though efforts will be directed more toward applied technology and engineering studies related to the Pilot Plant. Beyond FY 83, the Pilot Plant detail design and construction will require significant increases in funding, since each plant is expected to cost in the order of $250 M. Throughout this period, DOE will continue to develop alternative ocean energy concepts including open cycle OTEC, waves, currents and salinity gradients, with expanded programs for those concepts showing significant promise. In summary, DOE's ocean energy program is placing primary emphasis on near-turn solutions to our nation's energy crisis while planning for other technologies with far term potential.

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OTEC 10 MWe POWER SYSTEM DIAGRAM

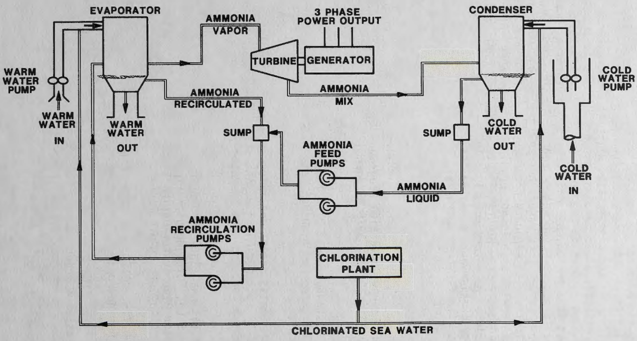


FIGURE 1

40 MW SPAR ARRANGEMENTS

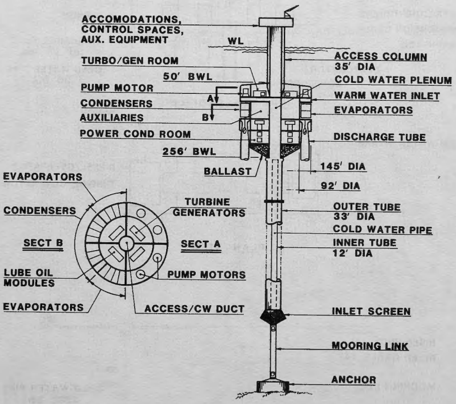


FIGURE 2

MOORED PLANTSHIP REFERENCE BASELINE

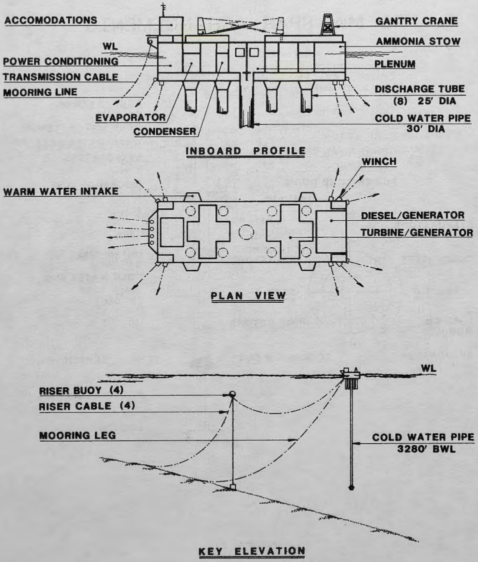


FIGURE 3

RISER SYSTEM CONCEPT

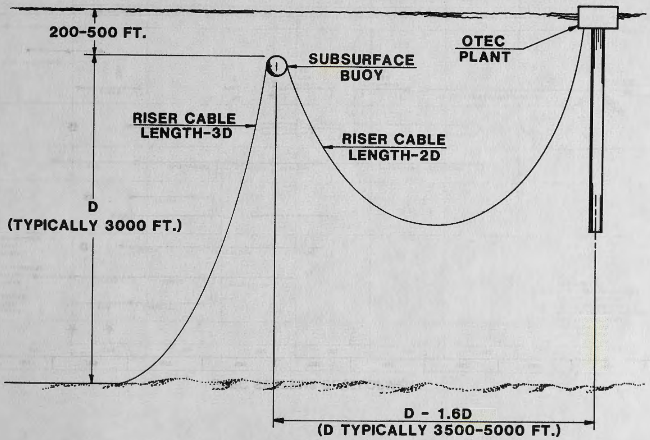


FIGURE 4

OTEC SYSTEMS DEVELOPMENT

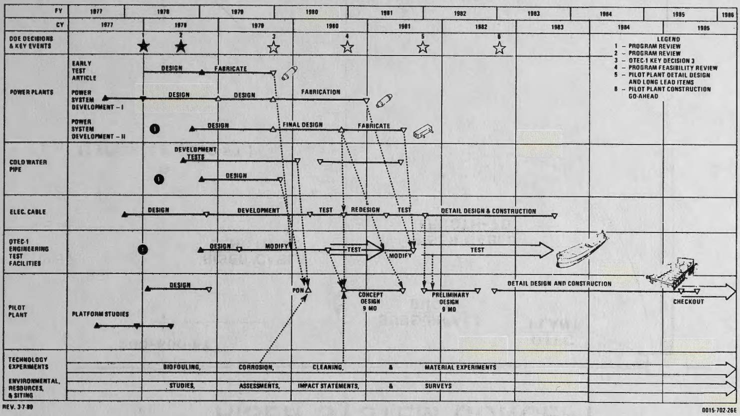


FIGURE 5

PUERTO RICO

COSTS OF ELECTRICITY FROM COMBINED CYCLE OIL AND 250 MWe OTEC PLANTS

(1976 DOLLARS)

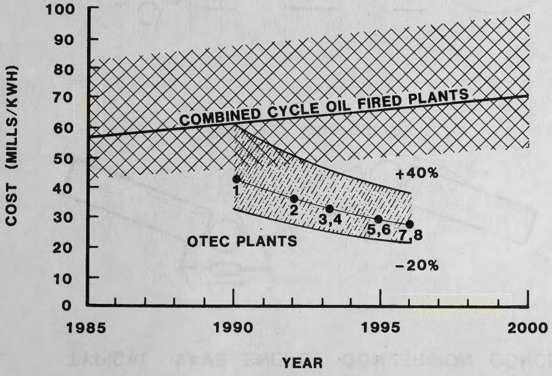
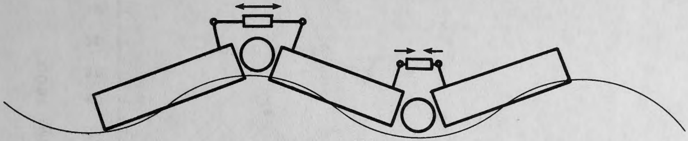
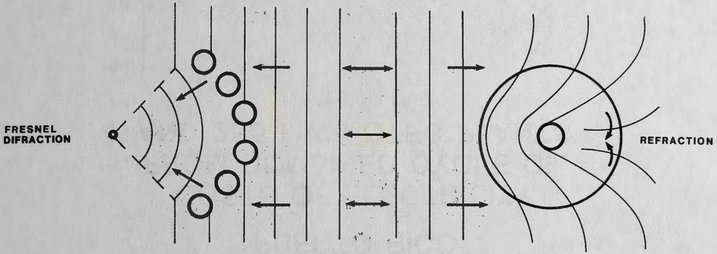


FIGURE 6

TYPICAL WAVE ENERGY CONVERSION CONCEPTS



Rotating Outriggers



Wave Focusing

FIGURE 7

TYPICAL WAVE ENERGY CONVERSION CONCEPTS

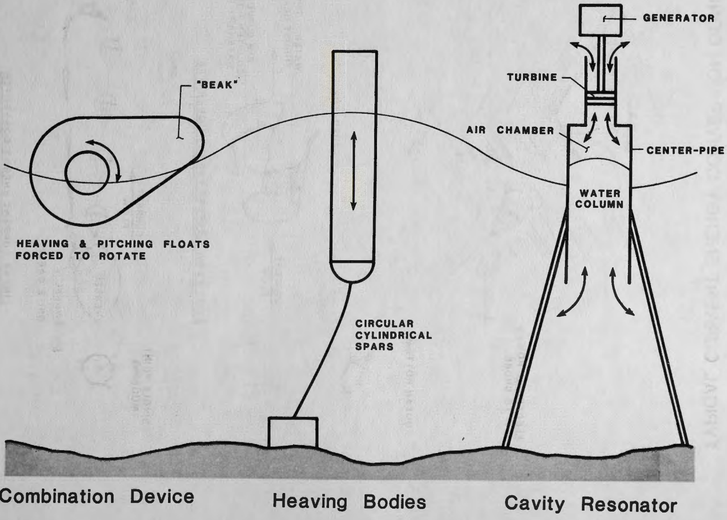
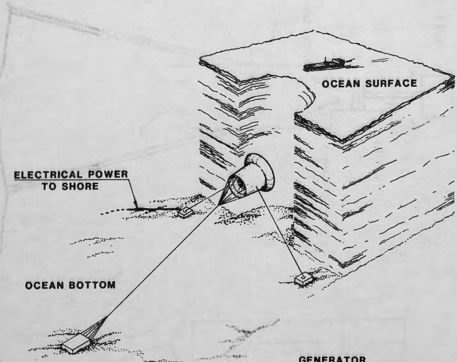
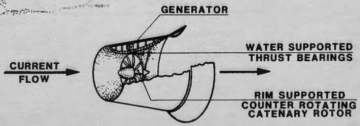


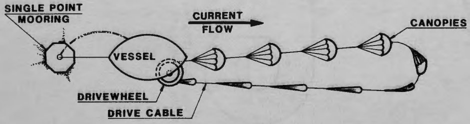
FIGURE 8

TYPICAL CURRENT ENERGY CONVERSION CONCEPTS





AXIAL FLOW CURRENT ENERGY CONVERTER



LINEAR CURRENT ENERGY CONVERTER

FIGURE 9