FEASIBILITY DESIGN STUDY
LAND-BASED OTEC PLANTS

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Final Report

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TABLE OF CONTENTS

	<u>Page Number</u>
TABLE OF CONTENTS	ii
LIST OF FIGURES	iii
LIST OF TABLES	vi
BIBLIOGRAPHY	viii
SECTION I <u>INTRODUCTION</u>	I-1
SECTION II <u>SUMMARY</u>	II-1
SECTION III <u>CONCLUSIONS AND RECOMMENDATIONS</u>	III-1
SECTION IV <u>SITES DESCRIPTION</u>	IV-1
SECTION V <u>POWER PLANT DESIGN</u>	V-1
SECTION VI <u>SEA WATER PIPES SYSTEM DESIGN</u>	VI-1
SECTION VII <u>CONSTRUCTION AND INSTALLATION</u>	VII-1
SECTION VIII <u>COST ESTIMATES</u>	VIII-1
SECTION IX <u>ALTERNATIVE CONCEPTS</u>	IX-1
APPENDICES	

LIST OF FIGURES

<u>Figure Number</u>	<u>Title</u>	<u>Page Number</u>
I-1	Zones of Investigation	I-4
I-2	OTEC Work Breakdown Structure	I-5
II-1	Land-Based OTEC Plant, Conceptual Arrangement	II-3
II-2	Cost Summary, OTEC Land-Based Power Plants	II-4
II-2A	Alternate Cost Summary, OTEC Land-Based Power Plants	II-5
II-3	Cost Summary, General Management (WBS 1.0)	II-6
II-4	Cost Summary, Design (WBS 2.0)	II-7
II-5	Cost Summary, Construction and Deployment (WBS 3.0)	II-8
II-5A	Alternate Cost Summary, Construction and Deployment (WBS 3.0)	II-9
II-6	Cost Summary, Operation and Support (WBS 4.0)	II-10
II-7	Program Schedule, Land-Based OTEC Plant, 10 MWe, Hawaii	II-13
II-8	Program Schedule, Land-Based OTEC Plant, 40 MWe, Hawaii	II-14
II-9	Program Schedule, Land-Based OTEC Plant, 10 MWe, Puerto Rico	II-15
II-10	Program Schedule, Land-Based OTEC Plant, 40 MWe, Puerto Rico	II-16
IV-1	Proposed Hawaii OTEC Site	IV-2
IV-2	Proposed Puerto Rico OTEC Site	IV-3

<u>Figure Number</u>	<u>Title</u>	<u>Page Number</u>
IV-3	Keahole Point, Hawaii	IV-5
IV-4	Keahole Point Lighthouse	IV-6
IV-5	Bottom Profile A, Keahole Point, Hawaii	IV-5
IV-6	Punta Yeguas, Puerto Rico	IV-15
IV-7	Puerto Yabucoa, Puerto Rico	IV-16
IV-8	Punta Tuna Area	IV-17
IV-9	Bottom Profile, Punta Yeguas, Puerto Rico	IV-19
V-1	40 MWe Power Plant Layout	V-5
V-2	Plan View, 40 MWe Power Plant	V-6
V-3	Elevation, 10 MWe Power Module	V-7
V-4	Plan View, 10 MWe Power Module	V-8
V-5	End Elevation, 10 MWe Power Module	V-10
V-6	End Elevation, 10 MWe Power Module	V-12
V-7	Side Elevation, 40 MWe Power Plant	V-13
V-8	10 MWe Power Plant Layout	V-14
V-9	Plan View, 10 MWe Power Plant	V-15
V-10	Elevation, 10 MWe Power Plant	V-16
V-11	Elevation, 10 MWe Power Plant	V-18
V-12	Plan View, 10 MWe Power Plant	V-20
V-13	Plan View, 10 MWe Power Module Lower Level	V-21
V-14	Plan View, 40 MWe Power Plant	V-22
V-15	40 MWe Power Plant Site Excavation	V-24
VI-1	Comparison of Seawater Pipe Lengths	VI-2
VI-2	Concrete Pipe Size Comparison	VI-3

<u>Figure Number</u>	<u>Title</u>	<u>Page Number</u>
VI-3	Eighteen Ft Pipe Fabrication Plant, San Onofre	VI-7
VI-4	Twenty-one Ft Pipe-Arizona Water Project	VI-8
VI-5	Pipe-Mobile and Concrete Pipe	VI-9
VI-6	Twenty-four Ft FRP Pipe Chimney Liner	VI-12
VI-7	Thirty-two Ft FRP Pipe Scrubber Tower	VI-13
VI-8	Category Definition, Pipe Installation	VI-17
VI-9	Single Length Pipe Installation Methods	VI-18
VI-10	Multiple Pipe Sections For Installation Methods	VI-19
VI-11	Cost/Tech Risk Factors For Buoyant Cold Water Pipe, Deep Water Zone, 40 MWe, off Hawaii	VI-20
VI-12	Cost/Tech Risk Factors; Heavy Cold Water Pipe, Deep Water Zone, 40 MWe, off Hawaii	VI-21
VI-13	Bottom Profile A, Keahole Point, Hawaii	VI-25
VI-14	Deadman Template, Cold Water Intake	VI-27
VI-15	Drilling for Pile Section	VI-28
VI-16	Lowering Pile Section	VI-29
VI-17	Pipe Section Post-Tensioning and Launch Facility	VI-30
VI-18	Typical Concrete Pipe Section	VI-31
VI-19	Pipe Section Remote Installation Technique	VI-33
VI-20	Transporting First Pipe Section	VI-34
VI-21	Bottom Profile, Punta Yeguas, Puerto Rico	VI-40
VI-22	Bottom Profile Showing Approximate Locations of Deadweight Anchors	VI-41
VI-23	Deadweight Anchor Deployment Method	VI-42

<u>Figure Number</u>	<u>Title</u>	<u>Page Number</u>
VI-24	Fabricated Spool with Alignment Bell and Butt Joint	VI-44
VI-25	FRP Pipe Wall Construction	VI-45
VI-26	FRP Flange and Joint Detail	VI-46
VI-27	Anchor Assembly	VI-47
VI-28	Buoyant FRP Pipe Installation, Step 1	VI-50
VI-29	Buoyant FRP Pipe Installation, Step 2	VI-51
VI-30	Buoyant FRP Pipe Installation, Step 3	VI-52
VI-31	Buoyant FRP Pipe Installation, Step 4	VI-54
VI-32	Locking Gate Assembly, FRP Pipe	VI-55
VI-33	Cold Water Intake, FRP Pipe	VI-56
VI-34	Typical Concrete Pipe Section, Puerto Rico	VI-57
VII-1	Construction Schedule, 40 MWe Plant, Hawaii	VII-15
VII-2	Construction Schedule, 10 MWe Plant, Hawaii	VII-16
VII-3	Construction Schedule, 40 MWe Plant, Puerto Rico	VII-17
VII-4	Construction Schedule, 10 MWe Plant, Puerto Rico	VII-18
IX-1	Barge Mounted, Land-Based OTEC Power Plant	IX-2
IX-2	Split Ammonia Loop Configuration	IX-4
IX-3	Schematic of Split Ammonia Cycle	IX-5

LIST OF TABLES

<u>Table Number</u>	<u>Title</u>	<u>Page Number</u>
IV-1	Deep Water Wave Parameters at Keahole Point - Most Probable 100-year Hurricane	IV-10

<u>Table Number</u>	<u>Title</u>	<u>Page Number</u>
IV-2	Shallow Water Wave Parameters at Keahole Point - Extreme 100-Year Hurricane	IV-10
IV-3	Maximum Current Velocity at Keahole Point - Most Probable 100-Year Hurricane	IV-11
IV-4	Current Velocity Profile in the Boundary Layer	IV-11
IV-5	Minimum and Maximum Temperatures with Depth-Keahole Point, Hawaii	IV-13
IV-6	Deep Water Wave Parameters at Punta Tuna - Most Probable 100-Year Hurricane	IV-20
IV-7	Shallow Water Wave Parameters at Punta Tuna - Extreme 100-Year Hurricane	IV-20
IV-8	Maximum Current Velocity at Punta Tuna - Most Probable 100-Year Hurricane	IV-24
IV-9	Minimum and Maximum Temperatures with Depth-Punta Tuna, Puerto Rico	IV-24
VI	Major Power Module Components	V-3
VI-1	Comparative Costs for Cold Water Pipe Materials	VI-5
VIII-1	Summary of Costs to the Fourth Level of the Work Breakdown Structure	VIII-24

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SECTION I

INTRODUCTION

This report summarizes the results of a feasibility study of land-based Ocean Thermal Energy Conversion (OTEC) power plants in two specific sizes for two specific sites in the United States. The study was carried out for the U. S. Department of Energy (DOE) by Deep Oil Technology, Inc., a subsidiary of the Fluor Corporation, under a subcontract to Value Engineering Company. Direct assistance was provided by Evans-Hamilton, Inc., also under a subcontract to Value Engineering Company.

OTEC CONCEPT

An OTEC plant makes use of the temperature difference between warm ocean surface water, and cold ocean water brought up from the depths. The warm water is used to boil a working fluid such as ammonia, while the cold water is used to condense it. By circulating the working fluid in a closed loop, turbines are turned and generators produce power. The power output is a function of the temperature difference, as well as the work expended to pump seawater through the condensers and evaporators, and working fluid through the power generator loop. OTEC is an attractive solar energy concept since it is pollution-free and can operate 24 hours a day.

The majority of OTEC investigations have been concerned with floating power plants, either for generation of power to be supplied to a land grid through a subsea cable, or for a "plant ship" which delivers an energy-intensive product such as ammonia or aluminum. However, a land-based OTEC power plant sited on the seacoast offers several advantages. First, no subsea cable is required; rather, the power is delivered directly to the local grid. Second, the problem of dynamic loading on the structure is avoided, resulting in a more reliable system. Third, construction of the plant, as well as maintenance

during operation, is a far simpler task.

PROBLEM DEFINITION

The purpose of this study has been to determine the feasibility of installing 10 MWe (MegaWatt-electric) and 40 MWe land-based OTEC demonstration power plants at two specific sites: Keahole Point on the western shore of the island of Hawaii; and Punta Tuna, on the southeast coast of the main island of Puerto Rico. In addition, the study has included development of design parameters, schedules and budgets for the design, construction and operation of these plants. Seawater systems (intake and discharge pipes) were to be sized so that flow losses were equivalent to those expected with a platform-based OTEC power plant. The power module (components and general arrangement) was established based on the TRW design. The entire task was to be completed in seven months, with preliminary budget established within ten weeks.

DATA BASE

During this study, it was necessary to determine quickly what work had been done that might be applicable, as well as to draw on the experience of others in areas related to the design and construction of similar installations. Value Engineering Company, with its extensive and growing OTEC library, was able to provide the major source of existing reports on past and current studies, particularly the recent work of TRW, Lockheed, and Westinghouse. The Fluor Corporation provided a major input to the information necessary for this task, particularly in the areas of cost estimating and large construction expertise. Major manufacturers of large-diameter pipes, in several different materials, were contacted for cost data and design information. A visit was made to the San Onofre nuclear power plant site in Southern California, where a major addition is underway, to observe the construction and installation of large-diameter cooling-water pipes. Finally, visits were made to both proposed sites,

allowing on-site discussions with University of Puerto Rico and Hawaii personnel and representatives of construction firms intimately familiar with local conditions.

Supporting unpublished documentation has been incorporated into project working paper, and retained.

METHOD OF INVESTIGATION

To conduct the feasibility design study, it was helpful to view the work as divided into three zones of investigation, shown in Figure I-1:

1) Land Zone; 2) Near Shore/Shallow Water Zone; 3) Deep Water Zone.

Each zone was then evaluated to identify any critical technical problems which might jeopardize the success of a landbased OTEC power plant. The identification of technical problem areas led to the development of preliminary conceptual solutions, upon which the early cost estimates were based.

As more site data were obtained, as well as more information on the construction and deployment of large-diameter pipes, the conceptual designs were altered and refined, leading to more detailed schedules and cost estimates. The work breakdown structure (WBS) shown in Figure I-2, provided by the DOE, formed the outline for cost estimating. In most cases, costs for the landbased OTEC were estimated to the fourth level of the WBS (e.g.: 3.2.1).

Figure I-1. Zones of Investigation

OTEC WORK BREAKDOWN STRUCTURE

AMOUNT IN 1978
\$100,000,000
\$100,000,000
\$100,000,000

Figure I-2. OTEC Work Breakdown Structure

SECTION II

SUMMARY

The general conceptual arrangement of a land-based OTEC power plant is shown in Figure II-1. Several important features are worth noting. First, regardless of plant size or specific geographical location, the plant should be situated as close to the shore line as possible to minimize the "lift" required for the seawater intakes and to allow the shortest possible seawater pipe runs. Second, the warm seawater intake is an open channel giving direct access to the warmest available water and saving the cost of a seawater pipe. The cold and warm seawater systems are parallel but completely separated, as this allows optimum placement of the condensers and evaporators, and because a mixed seawater discharge (cold and warm discharge combined) could lead to significant biofouling problems. On each side of the plant, separate intake and discharge plenums assure low water velocities and hence minimum flow losses. Since the seawater systems are open to atmospheric pressure, the heat exchangers are immersed entirely below sea level so that no head loss is experienced. As the illustration shows, the plant is designed around 10 MWe (net) power modules, with the ammonia cycle loop and power generating components directly in line between the condenser and evaporator, thus reducing piping requirements. Power lines are led from each generator back through the central area to a substation on the land side of the plant. The "repeated module" layout facilitates the use of an overhead crane system for component servicing and changeout. Finally, the simplicity of the plant layout allows future limited expansion, as well as providing the capability for shutting down a single module for servicing or when average demand for power is reduced.

While the plants in Hawaii and Puerto Rico would be different due to the unique physical characteristics of each site, the land based OTEC power plant concept is generally the same. The major differences are due to the soil conditions and the ocean bottom profiles. In Hawaii, the

Keahole Point site consists largely of hard lava rock both onshore and on the ocean bottom. The presence of the lava rock requires that the power plant components (except heat exchangers and seawater pumps) be located on the land surface. This is due to the high cost of blasting and excavating, as well as the difficulties posed by the porosity of the lava rock allowing seawater to percolate into any foundation below sea level. In contrast, the Punta Tuna area in Puerto Rico apparently consists of soil and rocks, which is easier to excavate and shore up against seawater intrusion. For consistency of design, however, the two power plant excavations will be similar, with deep troughs only for the seawater plenums. Offshore, the Hawaii bottom profile leads to a minimum of near-shore trenching to protect the seawater pipes. In deep water, the bottom slope appears smooth with a reasonably constant angle, allowing concrete pipe to rest on the bottom with the compressive loading supported by a bottom termination on the cold water intake pipe. In Puerto Rico, however, the bottom is shallow and flat for about a mile offshore, requiring extensive trenching to bury the concrete pipes for protection from the ocean waves. After the transition to the deep water slope, the bottom appears too rough and variable to adequately support a concrete pipe. For this reason, a buoyant fiberglass reinforced plastic (FRP) pipe will be used for deep water section of the cold water intake pipe, anchored to the ocean bottom at several points. The two different pipe designs therefore require two distinctly different installation techniques.

The estimated costs for the 10 and 40 MWe land-based OTEC power plants in Hawaii and Puerto Rico are summarized in Figures II-2 through II-6. The total costs are shown in Figure II-2. These costs are in 1980 dollars, assuming a 7-percent rate of inflation per year, 1978-1980. An overall 10-percent contingency is added and is included in the system total. Operation and support costs are included for each plant for 10 years after completion of construction. The installed cost (sum of WBS elements 1.0, 2.0 and 3.0) is also shown in dollars per kilowatt for

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PROJECT: 40 Mw OTEC POWER PLANT FIGURE II-1					

Figure II-1 Land-Based OTEC Plant, Conceptual Arrangement

	10 MWe		40 MWe	
	Hawaii	Puerto Rico	Hawaii	Puerto Rico
1.0 General Management	4.2	4.5	4.4	4.5
2.0 Design	3.5	3.6	3.5	3.6
3.0 Construction and Deployment	78.3	100.3	150.8	183.8
4.0 Operation and Support	10.7	10.7	15.7	15.7
OTEC System (Total)*	106.4	131.0	191.8	228.4
Installed Cost	\$9270/KW	\$11,740/KW	\$4320/KW	\$5230/KW

*Includes 10 Percent Contingency Allowance

Note: All Figures Except "Installed Cost" are in Millions of Dollars (1980)

Figure II-2. Cost Summary, OTEC Land-Based Power Plants

	10 MWe		40 MWe	
	Hawaii	Puerto Rico	Hawaii	Puerto Rico
1.0 General Management	4.2	4.5	4.4	4.5
2.0 Design	3.5	3.6	3.5	3.6
3.0 Construction and Deployment	<u>86.7</u>	<u>108.7</u>	<u>189.2</u>	<u>202.2</u>
4.0 Operation and Support	10.7	10.7	15.7	15.7
OTEC System (Total)*	<u>115.6</u>	<u>140.2</u>	<u>234.1</u>	<u>270.1</u>
Installed Cost	<u>\$10,190/KW</u>	<u>\$12,660/KW</u>	<u>\$5480/KW</u>	<u>\$6400/KW</u>

*Includes 10 Percent Contingency Allowance

Note: All Figures Except "Installed Cost" are in Millions of Dollars (1980)

Figure II-2A. Alternate Cost Summary, OTEC Land-Based Power Plants

Millions of Dollars (1980)

	10 MWe		40 MWe	
	Hawaii	Puerto Rico	Hawaii	Puerto Rico
1.1 Design Phase	0.9	0.9	0.9	0.9
1.2 Acquisition/Construction and Deployment Stage	1.6	1.9	1.8	1.9
1.3 System Operations and Support Phase	1.7	1.7	1.7	1.7
General Management (Total)	4.2	4.5	4.4	4.5

Figure II-3. Cost Summary, General Management (WBS 1.0)

Millions of Dollars (1980)				
	10 MWe		40 MWe	
	Hawaii	Puerto Rico	Hawaii	Puerto Rico
2.1 Conceptual Design	*	*	*	*
2.2 Preliminary Design	1.5	1.5	1.5	1.5
2.3 Contract Design	2.0	2.1	2.0	2.1
Design (Total)	3.5	3.6	3.5	3.6

*Assumed to be Completed

Figure II-4. Cost Summary, Design (WBS 2.0)

Millions of Dollars (1980)

	10 MWe		40 MWe	
	Hawaii	Puerto Rico	Hawaii	Puerto Rico
3.1 Platform System	N/A	N/A	N/A	N/A
3.2 Land-Based Containment System	9.2	7.4	18.0	12.8
3.3 Cold Water Pipe System	20.7	38.6	32.0	59.7
3.4 Warm Water Pipe System	2.3	10.7	3.6	16.8
3.5 Power System	13.6	13.6	49.6	49.6
3.6 Energy Transfer System	0.5	0.5	1.5	1.5
3.7 Energy Utilization System	N/A	N/A	N/A	N/A
3.8 Acceptance Testing	2.4	2.4	3.4	3.4
3.9 Deployment Services	24.2	18.7	36.6	31.2
3.10 Industrial Facilities	*	2.1	*	2.1
3.11 Engineering & Detail Design	5.4	6.3	6.1	6.7
Construction & Deployment (Total)	78.3	100.3	150.8	183.8

*Included in Item 3.2

Figure II-5. Cost Summary, Construction and Deployment (WBS 3.0)

Millions of Dollars (1980)

	10 MWe		40 MWe	
	Hawaii	Puerto Rico	Hawaii	Puerto Rico
3.1 Platform System	N/A	N/A	N/A	N/A
3.2 Land-Based Containment System	9.2	7.4	18.0	12.8
3.3 Cold Water Pipe System	20.7	38.6	32.0	59.7
3.4 Warm Water Pipe System	2.3	10.7	3.6	16.8
3.5 Power System	<u>22.0</u>	<u>22.0</u>	<u>88.0</u>	<u>88.0</u>
3.6 Energy Transfer System	<u>0.5</u>	<u>0.5</u>	<u>1.5</u>	<u>1.5</u>
3.7 Energy Utilization System	N/A	N/A	N/A	N/A
3.8 Acceptance Testing	2.4	2.4	3.4	3.4
3.9 Deployment Services	24.2	18.7	36.6	31.2
3.10 Industrial Facilities	*	2.1	*	2.1
3.11 Engineering & Detail Design	5.4	6.3	6.1	6.7
Construction & Deployment (Total)	<u>86.7</u>	<u>108.7</u>	<u>189.2</u>	<u>222.2</u>

*Included in Item 3.2

Figure II-5A. Alternate Cost Summary, Construction and Deployment (WBS 3.0)

Millions of Dollars (1980)

	10 MWe		40 MWe	
	Hawaii	Puerto Rico	Hawaii	Puerto Rico
4.1 Operational Support, Offshore	N/A	N/A	N/A	N/A
4.2 Operational Support, Onshore	10.7	10.7	15.7	15.7
4.3 OTEC System Tests	*	*	*	*
4.4 Refit and Modification	Not Costed	Not Costed	Not Costed	Not Costed
4.5 System Disposal	0.0	0.0	0.0	0.0
Operation and Support (Total)	10.7	10.7	15.7	15.7

*Included in Items 1.3 and 3.2

Figure II-6. Cost Summary, Operation and Support. (WBS 4.0)

comparative purposes; this cost does not include the 10 percent contingency. At the recent direction of the Department of Energy, and for the purposes of consistency, Power System costs (WBS 3.5) have been adjusted to \$22.0 M for the 10 MW design and \$88.0 M for the 40 MW design. These costs reflect the uncertainties of a first system, and particularly new (increased) expected heat exchanger costs. These adjustments are shown in Figures II-2A and II-5A which follow the figures showing the unadjusted costs. As with the previous costs, profit is assumed included in the basic cost, and a 10-percent contingency allowance added to the final total. The costs shown in Figures II-3 through II-6 follow the Work Breakdown Structure to the third level. Costs to the fourth level of the WBS, together with costing methodology and background data, may be found in Section VIII of this report. The major cost difference between 10 and 40 MWe plant sizes is the additional cost of power module components. The major cost difference between the two proposed sites is the cost associated with the considerably longer pipe runs in Puerto Rico, as well as the additional cost of the FRP pipe. Figures II-7 through II-10 show the estimated design, construction and operation schedules for the land-based OTEC plants. Note that the Conceptual Design phase is assumed to be completed, and that the design phase will take approximately 20 months regardless of plant size or location. Note also that the construction phase, including detail design, covers a period of approximately 3 years.

There are several distinct advantages of a land-based OTEC power plant, particularly when compared with its floating, platform-mounted counterpart:

1. Because most of the design and construction work is similar to jobs already accomplished, with the exception of the deep water pipe installation, there should be a high confidence in the cost estimates with a lower risk of cost overruns.
2. The land-based OTEC plant alleviates the power transmission problem, since the power is delivered directly from the

*Assumed to be Completed

Figure II-7. Program Schedule, Land-Based OTEC Plant, 10 MWe, Hawaii

*Assumed to be Completed

Figure II-8. Program Schedule, Land-Based OTEC Plant, 40 MWe, Hawaii

*Assumed to be Completed

Figure II-9. Program Schedule, Land-Based OTEC Plant, 10 MWe, Puerto Rico

*Assumed to be Completed

Figure II-10. Program Schedule, Land-Based OTEC Plant, 40 MWe, Puerto Rico

generators to the substation without a lengthy power cable and its associated losses.

3. The time necessary for detail design and construction of the land-based plant is approximately 3 years, significantly less than for a floating plant.
4. Since the plant construction will utilize primarily a local labor force, the economies of Hawaii and/or Puerto Rico will benefit directly.
5. Operating costs for a land-based OTEC plant are minimal, since very few personnel are required for operation and maintenance.
6. Component change-out and repair is greatly facilitated as compared to a floating plant.
7. Since there are virtually no dynamic considerations with a land-based plant, availability should be nearly 100 percent with no down-time due to weather.

SECTION III

CONCLUSIONS AND RECOMMENDATIONS

This study concludes that OTEC power plants can be sited on land adjacent to deep ocean water, with sufficient thermal gradient, and generate electric power in the 10 MW_e to 40 MW_e range. The designs, cost estimates, and construction schedules are quite site specific, requiring a detailed knowledge of the site's environmental and engineering properties, both on and off shore. The Keahole point, Hawaii, and Punta Tuna, Puerto Rico sites are both acceptable candidates for land-based 10 to 40 MW_e OTEC plants.

The construction assembly and installation of power plant modules on land present no unusual or difficult problems. It is completely within the state of the art. The most cost effective construction means depends primarily on the rock or soil properties and the related excavation methods. The major construction costs is the excavation below sea level of the area required to submerge heat exchanger and sea water pump intakes. Construction is closely related to that required for building a small boat harbor. The volcanic materials present at Keahole Point, require drilling and blasting at a relatively high cost. The coarse rock and sand materials, present in the Punta Tuna area, may be excavated at a lower cost, using dragline and scrapper methods primarily. Offshore excavation for sea water pipe trenches in the surf zone requires the same types of excavation as on land for each site. The length of trenches and therefore, quantity of material to be excavated, is considerably more at the Puerto Rico site.

The deep water portion of the cold water intake pipes present the most significant engineering aspect of a land-based OTEC plant. Though pipes are being fabricated for water transport of near the large 30-foot diameter required, they have only been installed in shallow, near shore water. Installation of both the 15-foot-and 30-foot-diameter pipes in deep water is beyond industry's currently demonstrated capability.

However, the conceptual solutions for installation developed in this study are thought to be workable, requiring only extensions of demonstrated industry accomplishments rather than new development. Concrete pipe, selected for the Hawaii location, can rest securely on the hard, relatively smooth sea floor. Drilled and cemented piling will be required to resist the gravity loads. FRP pipe, selected for the Puerto Rican location, is buoyant and can be anchored at a position above the highly irregular steeply inclined sea floor. Though the required diameters of FRP pipe have been fabricated, the required lengths have not. Furthermore, the installation method proposed is novel and will require some further analysis, development, and testing.

These methods were developed after concluding that preparing or smoothing a bed for the cold water pipe in these deep waters was probably not feasible, and is at best, prohibitively expensive. The shallow water pipeline materials and installation methods were selected primarily on the basis of cost, and modest extensions of demonstrated pipe construction and installation methods. Once installed, plant start-up, operation, and maintenance should prove less costly and more reliable than for a similar floating plant.

Since it is concluded that land-based OTEC plants are feasible, and that several advantages over floating OTEC plants are indicated, it is recommended that work continue on the plant configuration presented herein. As the deep water portion of the cold water intake pipe is the only aspect of plant design and construction that is not backed by a solid base of industry experience, it is recommended that the design of the deep water portion of the pipe be further developed so that its feasibility can be established with confidence. Once this is accomplished, the following further work is recommended:

- o The preliminary design phase be initiated based on this Feasibility Design Study at one or more specifically

designated plant sites.

- o A brief study shall be conducted to evaluate the feasibility of the alternative plant siting concepts outlined in Section IX.
- o If a highly irregular, steeply inclined slope is indicated at a selected plant site, analysis and design of a buoyant (probably FRP) cold water intake pipe should be accomplished.
- o Detailed offshore bathymetry and seafloor engineering properties should be obtained for one or more specific sites.

SECTION IV SITE DESCRIPTION

GENERAL

The success of a land-based OTEC demonstration power plant depends greatly on careful and studied selection of the plant site. As the OTEC process utilizes warm ocean surface water to vaporize ammonia and cold deep ocean water to condense the ammonia, the site requires deep water and a 20°C minimum ocean thermal gradient close to shore. Two general locations, previously identified, were chosen by the DOE for this study: Hawaii (Keahole Point, on the western shore of the island of Hawaii), and Puerto Rico (Punta Tuna, on the southeast coast of the island of Puerto Rico). These sites are shown in Figures IV-1 and IV-2.

Since this study is primarily to determine the feasibility of a land-based OTEC power plant, no new investigations were carried out to develop new environmental data. However, the meteorological/oceanographic data for the two sites were collated from available studies of the Environmental and Resource Assessment Branch of DOE; these data are presented in a report written by Evans-Hamilton, Inc., Reference 18. Two of the most important other sources were (1) the "Environmental Impact Statement for the Natural Energy Laboratory of Hawaii at Keahole Point, Hawaii (Phase I)", prepared for the Research Corporation of the University of Hawaii (December 1976) and (2) "Preliminary Conceptual Design for PROTEC", prepared for the Puerto Rico Water Resources Authority by Black and Veatch (1978). In addition, contacts were made with people familiar with each site to further discuss details of the data acquired. Finally, an inspection visit was made by project personnel, first to the Hawaii site and then to the Puerto Rico site; this perspective proved invaluable to the development of the design concepts and cost estimates for the OTEC power plants.

2503A

Figure IV-1. Proposed Hawaii OTEC Site

Figure IV-2. Proposed Puerto Rico OTEC Site

From an examination of the data, several conclusions may be drawn. First, design of a land-based OTEC plant must be site specific; that is, local conditions dictate the location of the power plant components, the seawater pipe design, and route along the seafloor, etc. Second, because of recent interest in the Hawaii site for development of a Natural Energy Laboratory, there is far more information available for this site than for the one in Puerto Rico. However, in both cases, much more detailed topographic, oceanographic, and bathymetric data must be obtained before a land-based OTEC plant may be constructed. Therefore, a "site survey" is required to be accomplished during the preliminary and contractual design phases. Finally, while the Hawaii site is already in government hands and dedicated to energy and environmental research, it appears that the land in Puerto Rico is presently owned by private interests and must be acquired prior to the construction phase of a land-based OTEC plant.

The site information is presented separately in the following sections for Hawaii and Puerto Rico.

Hawaii

Keahole Point, the proposed site of the Hawaii land-based OTEC demonstration plant, is located on the western coast of the main island of Hawaii. Figures IV-3 and IV-4 give some idea of the local conditions. This site is uniquely suited to development for an OTEC plant, both because of the proximity of a large thermal gradient in the ocean waters and because the site for the Natural Energy Laboratory of Hawaii (NELH) about 240 acres, is owned by the State of Hawaii. In addition, a major commercial airport and coastal highway provide direct access, while there are also a small-boat harbor 4 miles to the south and a deep-water harbor at Kawaihae about 25 miles to the north. For reference, the following charts were used in this study.

Figure IV-3. Keahole Point, Hawaii

2448A

Figure IV-4. Keahole Point Lighthouse

NOAA-N.O.S. 19327 West Coast of Hawaii, Cook Pt. to Upolu Pt.
(July 9, 1977)

USGS NE5-1,5 Hawaii, Hawaii (1975)

USGS Keahole Point Quadrangle (1959)

Site Selection Bathymetry Survey, Keahole Point. Hawaii,
Hawaii

(Tech. Report No. 43, University of Hawaii, James K. K. Look
Laboratory of Oceanographic Engineering, December 1977).

Sea Level Elevations

The mean tide range near Keahole Point is 1.4 feet, while the diurnal range is 2.1 feet. While storm surge data is limited, the controlling factor for design water levels is the height of tsunamis. Study of a tsunami in 1946 indicates a height at the proposed site of about 11 feet; a recent study projects a 100-year tsunami of 15 feet, based on an unverified reference. A 50-year storm tide due to hurricane is predicted to be only 0.6 feet. Wave run-up is predicted at a maximum of 500 feet from the shoreline.

Meteorology

Offshore trade wind data shows that the trade wind normally blows at a mean speed of about 13 knots, and 80 percent of the time from between the northeast and the southeast. The highest winds generally occur from November to April, with January the worst month. The most probable 100-year hurricane would result in a maximum design wind of 60 knots, and a maximum gust of 87 knots. However, due to the large volcanic masses on the island, winds at Keahole Point will normally be light and offshore at night, turning to southwesterly (onshore) during the day averaging 8-10 knots. The coastline is relatively cloud-free, with temperatures averaging nearly 80° F.

Oceanography

The bottom profile at the site is one of the most important engineering aspects, as it determines the design and installation of the seawater pipe system. To determine the bottom profile off Keahole Point, shown in Figure IV-5, the Bathymetry Survey chart from the University of Hawaii was used. A transect was made, running from the lighthouse on a bearing 20° South of West (approximately perpendicular to the bottom contours), and the profile generated from the contours at 50-foot depth intervals. From the published reports, and conversations with Dr. Edward Noda of the University of Hawaii, it appears that the bottom conditions are generally ideal for the construction of a pipeline. With the exception of some major (up to 20 feet high) rock outcroppings where the deep water slope begins, the bottom is generally flat hard volcanic rock (basalt) covered by a thin veneer of sand. The near-shore area is primarily lava base with sand pockets, scattered large irregular rocks and finger corals.

Waves are of significance, particularly during installation of the seawater pipe system. Deep water parameters are presented in Table IV-1 for the most probable 100-year hurricane. Shallow water wave parameters are presented in Table IV-2 for the extreme 100-year hurricane, including refraction and shoaling effects. Typical wave heights show generally mild conditions: wave heights less than 4 feet occur 54.6 percent of the time; wave heights less than 7 feet occur 89.4 percent of the time; wave heights less than 12 feet occur 99.0 percent of the time.

Table IV-3 summarizes the estimated maximum current velocity for deep water during the 100-year most probable hurricane. For boundary layer effects on the current near the bottom, (e.g. for calculating current drag on a bottom-laid pipe), Table IV-4 may be used. However, theoretical maximum current velocities may be low by 50 percent or more. Near-bottom current velocities are extremely difficult to

Table IV-1. Deep Water Wave Parameters at Keahole Point-
Most Probable 100-Year Hurricane

Average Height (Feet)	18.8
Significant Height (Feet)	30.0
Maximum Height (Feet)	54.0
Average Period (Seconds)	10.0
Significant Period (Seconds)	11.0
Model Period (Seconds)	11.6

Table IV-2. Shallow Water Wave Parameters at Keahole Point-
Extreme 100-Year Hurricane

<u>Depth (Feet)</u>	<u>Maximum Wave Height (Feet)</u>
370	64.6
300	63.1
200	60.7
100	59.1
75	60.2 (Breaking Wave)
50	40.1 (Breaking Wave)
25	19.6 (Breaking Wave)
10	7.9 (Breaking Wave)

Table IV-3. Maximum Current Velocity at Keahole Point-
Most Probable 100-Year Hurricane

<u>Water Depth (Feet)</u>	<u>Current Velocity (Knots)</u>
0	2.1
130	1.8
260	1.5
660	1.1
1310	0.8
1970	0.6
2620	0.5
3280	0.5

Table IV-4. Current Velocity Profile in the Boundary Layer

<u>Distance Above Bottom (Feet)</u>	<u>Percent of Free Stream Velocity</u>
33	99
25	95
15	89
5	76
3	70
2	65
1	56
0	0

predict, therefore long-term measurements along the proposed route must be made before good pipe design criteria may be developed. Tidal currents generally flow in a northeast-southwest direction, with a maximum design value of 0.4 knots and an average value of 0.2 knots. In addition, the presence of a strong flow in a generally northward direction, averaging about 0.3 knots, has been detected; combining with the flood tide, currents of over a knot may be anticipated.

Table IV-5 summarizes the available data on maximum and minimum temperatures along the proposed pipe route. Using a surface intake for warm seawater and a 3000-foot depth for cold seawater, the maximum temperature differential should be about 41⁰ F in September, while the minimum should be about 35⁰ F in February.

Corrosion and biofouling are being heavily studied for the offshore OTEC sites, and little preliminary information is available. These areas impact particularly the selection of materials, and effluent discharge, and should be covered thoroughly when more information can be obtained, perhaps during preliminary design.

Puerto Rico

Punta Tuna, the proposed site of the Puerto Rico land-based OTEC demonstration plant, is located on the southeast coast of the island of Puerto Rico. While early information supported the choice of this point, due to its proximity to deep water with a pronounced-thermal gradient, subsequent data revealed that the seawater pipeline route would cross an ecologically valuable reef. Since this probably would not be permitted, the nearby coastline was examined for a good alternative site, leading to the selection of Punta Yeguas about 4 miles to the east. A similar bottom profile exists at the latter location, without an interfering reef, as well as a sheltered cove ideally suited for the OTEC plant. In addition, just to the north at Puerto Yabucoa is a deep water harbor (used by Sun Shipping Company

Table IV-5. Minimum and Maximum Temperatures with
Depth-Keahole Point, Hawaii

<u>Water Depth (Feet)</u>	<u>Temperatures (^oF)</u>	
	<u>Maximum</u>	<u>Minimum</u>
0	83	73
70	83	72
130	83	69
200	82	65
260	82	64
330	82	62
660	72	54
980	55	49
1310	49	45
1640	45	43
2300	42	41
2950	41	40
3610	39	39

oil tankers and a large expanse of flat industrial land, where pipe manufacturing could be carried out. Figure IV-6 shows an aerial view of Punta Yeguas with the cove just beyond; Figure IV-7 shows a view of the industrial area at Puerto Yabucoa. Figure IV-8 shows the outline of the coastline in the region, together with several important features. For reference, the following charts were used in this study:

USGS, Puerto Rico, E Islas Limitrofes (1951)

USGS, Punta Tuna Quadrangle (1960)

USGS, Punta Guayanes Quadrangle (1960)

N.O.S. Hydrographic "Boat Sheets" No. 9607 and 9608 (1976).

Sea Level Elevations

The diurnal tide in the Punta Tuna area is only 1.0 feet, with a typical annual maximum of about 1.8 feet. Because the southeast coast of Puerto Rico is subjected directly to hurricanes and tropical storm, storm surge will be the most important water level design parameter; for the Punta Tuna area, the 100-year storm surge (including effects of tide) is estimated to be 7.5 feet. While this area is reported to be a seismically active zone, no tsunami data has been found for this report.

Meteorology

Offshore winds along the south coast of Puerto Rico blow at a mean speed of about 13 knots, and 93 percent of the time from between the northeast and the southeast. The highest winds generally occur from February to July, with March the worst month. However, cyclonic winds may be expected well over a hundred times in 100 years, with the greatest possibility in August and September. The most probable 100-year hurricane would result in a maximum design wind of 85 knots, and a maximum gust of 123 knots. Local mountainous terrain may mitigate or alter these wind conditions.

Figure IV-6. Punta Yequas, Puerto Rico

Figure IV-7. Puerto Yabucoa, Puerto Rico

Oceanography

Despite its importance in the design and installation of the seawater pipe system, a reliable estimate of the detailed bottom profile was not found for this study. Only limited deep water bathymetry is available for this area; for this reason, the profile shown in Figure IV-9 was developed from the chart data previously referenced. Extreme caution should be exercised when using this profile, and detailed pipe design should await the results of site survey work to be done during the Preliminary Design phase. From the published reports, and conversations with Drs. Don Sasscer and Gary Goldman of the Center for Energy and Environment Research, it appears that the bottom conditions are quite hostile, described as "the worst kind of mountain-climbing terrain imaginable". In the shallower waters extending roughly a mile offshore, the bottom consists of a jumble of rock, gravel and shell fragments interspersed with coral. Beyond this point, as the profile descends steeply to deep water, the bottom is hard and consists of clay, sand, mud and coral.

Deep water wave parameters are presented in Table IV-6 for the most probable 100-year hurricane. Shallow water wave parameters are presented in Table IV-7 for the extreme 100-year hurricane, including the effects of refraction and shoaling. Typical wave heights show even milder conditions than in Hawaii: wave heights less than 4 feet occur 68.6 percent of the time; wave heights less than 7 feet occur 95.9 percent of the time; wave heights less than 12 feet occur 99.8 percent of the time.

Table IV-8 summarizes the estimated maximum current velocity for deep water near the proposed site during the most probable 100-year hurricane. These velocities include normal tidal and geostrophic current components. For boundary layer effects on the current near the bottom,

Figure IV-9. Bottom Profile, Punta Yeguas, Puerto Rico
IV-19

Table IV-6. Deep Water Wave Parameters at Punta Tuna-
Most Probable 100-Year Hurricane

Average Height (Feet)	23.1
Significant Height (Feet)	36.9
Maximum Height (Feet)	66.4
Average Period (Seconds)	10.8
Significant Period (Seconds)	11.9
Model Period (Seconds)	12.6

Table IV-7. Shallow Water Wave Parameters at Punta
Tuna-Extreme 100-Year Hurricane

<u>Depth (Feet)</u>	<u>Maximum Wave Height (Feet)</u>
430	79.6
300	76.7
150	72.7
92	73.9 (Breaking Wave)
75	58.8
50	39.7
25	19.6
10	7.6

Table IV-4 in the previous section may be used. As in Hawaii, caution should be used, as these currents are quite difficult to predict; long-term current measurements along the proposed pipe route are essential to an adequate design. From data in the general region, a westerly flow can be expected running up to 2 knots at the surface. However, surface current reversal (to the east) can be expected near the site about 50 percent of the time. Subsurface currents are characterized by large differences in direction with depth. Maximum deep water currents observed were 0.3 knots at 3372 feet and 0.4 knots at 4666 feet, both taken about 14 miles east of Punta Tuna.

Table IV-9 summarizes the available data on maximum and minimum temperatures along the proposed pipe route. Using a surface intake of warm seawater and a 3000-foot depth for cold seawater, the maximum temperature differential should be about 42° F in September, while the minimum should be about 36° F in March.

As with Hawaii, corrosion and biofouling are being studied for the proposed offshore OTEC sites, and little preliminary information is available.

Table IV-8. Maximum Current Velocity at Punta Tuna--
Most Probable 100-Year Hurricane

<u>Water Depth (Feet)</u>	<u>Current Velocity (Knots)</u>
0	2.1
130	1.6
260	0.7
660	0.5
1310	0.5
1970	0.4
2620	0.2
3280	0.4

Table IV-9. Minimum and Maximum Temperatures with
Depth--Punta Tuna, Puerto Rico

<u>Water Depth (Feet)</u>	<u>Temperatures (°F)</u>	
	<u>Maximum</u>	<u>Minimum</u>
0	87	76
70	87	76
130	87	75
200	85	74
260	83	73
330	81	72
660	71	64
980	65	58
1310	61	53
1640	56	50
2300	48	44
2950	44	42
3610	41	40

SECTION V

POWER PLANT DESIGN

The conceptual design of the power system for a land-based OTEC power plant is based on work performed by TRW in their presentation to the DOE "OTEC Power System Development", Intermediate Design Review, 5 June 1978 (reference 15); and the TRW report on OTEC power system development of 12 May 1978 (reference 14). The reports prepared by Lockheed (reference 5, 6) and by Westinghouse (reference 16, 17) on OTEC power system development, were also studied. It was decided, with the concurrence of the DOE, that this feasibility design would be based on the 10 MWe power module designs developed by TRW.

The TRW power system includes heat exchangers of a unique design. The shell and tube heat exchangers feature vertical orientation of the titanium seawater tubes with a vertical, falling ammonia film on the shell side. The tubes are formed with longitudinal flutes to enhance heat transfer. In addition, the heat exchangers feature an open top design with a large plenum or water box above the tubes. This enables ready access to the tubes for cleaning by means of a multiple-spindle, mechanical brush. The simple, open top design of the water box means, however, that the heat exchangers must be installed somewhat below sea level in excavated troughs or trenches. This must be done in order to avoid the large power losses which would be incurred if the great quantities of water required for the OTEC cycle had to be pumped above sea level to the exchangers.

The major components in each 10 MWe power module in a land-based OTEC plant would be essentially identical to the components shown in the 10 or 40 MWe TRW floating plant.

The spatial arrangement of those components within each power module will be slightly different, however, to account for the differences between a floating platform and a land-based plant layout. In some cases, certain simplifications can be made to the power module because of its land-based environment. For example, the mounting and support structure required for the heat exchangers can be lightened because of the absence from these structures of dynamic loading due to floating plant motions.

The approximate dimensions and weights of the major power plant components are shown in Table V-1.

The 40 MWe and 10 MWe OTEC power plants are described in further detail in the following sections.

40 MWe POWER PLANT LAYOUT

Figure V-1 shows the proposed general layout of a 40 MWe land-based OTEC power plant. The power plant would be situated as close to the shoreline as possible to minimize the lengths of large diameter pipe required for the seawater system. Pipes would be required for both the intake and discharge cold water lines, but only for the discharge line on the warm water side, warm intake water being pumped directly from the near shore surface waters via an open channel.

As shown in Figure V-1, the power plant consists of four 10 MWe power modules situated between the warm water and cold water pipe systems. The electric power conditioning equipment would be housed

Table V-1. Major Power Module Components

<u>Item</u>	<u>Weight (Pounds)</u>	<u>Dimensions (Feet)</u>
Condenser	566,000	25 dia. x 46 H
Evaporator	570,000	25 dia. x 46 H
Warm Water Pump	160,000	12 lower dia. x 18 upper dia x 36 high
Cold Water Pump	160,000	same as above
Warm Water Pump Motor	56,000	7 dia. x 14 H
Cold Water Pump Motor	59,000	7 dia. x 14 H
Ammonia Feed Pump	5,300	7 L x 7½ W x 4 H
Ammonia Feed Pump Motor	2,350	6 L x 5W x 4 H
Ammonia Recirculation Pump	2,130	8 L x 5 W x 5 H
Ammonia Recirculation Pump Motor	320	5½ L x 4½ W x 4 H
Turbine-Generator Assembly	176,000	32 L x 10 W x 12 H
Lubrication/Cooling Equipment	32,000	14 L x 10 W x 7 H
Evaporator Sump Tank	11,000	10 dia. x 22 H
Condenser Sump Tank	11,000	10 dia. x 22 H
Filter Screen	6,400	6 dia. x 6 H

in a sub-station behind the power modules. Areas designated for nitrogen and ammonia storage, maintenance equipment and general storage yards, an office and parking lot are also shown in the layout. This arrangement allows for the simplest possible seawater pipe installation method, and also provides for a straightforward, efficient layout of power module components.

A more detailed plan view of the 40 MWe power plant is shown in Figure V-2. Design features of a typical 10 MWe power module are presented in Figures V-3 and V-4 which show the major components of a power module in end elevation and plan view, respectively.

When the OTEC power plant is in operation, warm water is drawn from the open intake channel by the bank of warm water pumps and pumped into the open plenum above the evaporators. The warm water then flows down through the evaporator tubes into the bottom of the discharge plenum and out through the warm water discharge pipeline.

Figure V-1. 40 MWe Power Plant Layout

Figure V-2. Plan View, 40 MWe Power Module

Figure V-3. Elevation, 10 MWe Power Module

Figure V-4. Plan View, 10 MWe Power Module

The warm water flowing through the evaporator causes the liquid ammonia on the shell side to vaporize. This pressurized ammonia vapor is ducted above ground level to the turbine where its energy is used to drive a generator. From the turbine exhaust, the ammonia vapor is ducted to the condenser, which is mounted below sea level in the cold water discharge plenum. Cold water is supplied to the condensers by the bank of cold water pumps, which is immersed in the cold water intake plenum.

Figure V-3 shows the relationship of the various operating levels in the warm water and cold water plenums. The seawater pumps, of course, must be sufficiently submerged below the nominal operating levels to insure against ventilation or cavitation at the impellers. The heat exchangers must also be submerged well below the operating levels in their respective water plenums to insure smooth flow and even distribution of seawater to all the tubes in the exchangers. Note that the operating level of cold water in the intake trough is a few feet below sea level. This is due to a combination of the density gradient effect in the ambient seawater column and the friction flow losses in the long, cold water intake pipe.

Figure V-5 shows an end elevation of the power plant as it would appear with walls and roof in place. This drawing, along with the plan view of Figure V-4, also shows the components of the liquid ammonia loop. The liquid ammonia sump tanks are mounted in the seawater plenums so that the operating level of the ammonia inside each tank is somewhat lower than the bottom of its respective heat exchanger. The feed pumps, recirculating pumps, filters, and associated piping and valving for the remainder of the ammonia loop are mounted at ground level, however, to save the cost of extensive excavation and to ease access and maintenance tasks.

Figure V-5. End Elevation, 10 MWe Power Module

Figure V-6 provides another end elevation view of the power plant showing the gaseous ammonia loop. This drawing also shows the overhead bridge cranes which will be used during the installation of power plant components and piping. Once the power plant is put into operation, the bridge cranes would be used to position the multiple-spindle, mechanical brushes over the heat exchangers during routine cleaning of the seawater tubes.

A side elevation of the power plant is shown in Figure V-7 which depicts the four warm water pumps immersed in the warm water intake trough. The warm water discharge pipe is also shown in this drawing. The pipe is shown in the bottom of a trench slanted downward at 10^0 , as it would be installed at the Keahole Point, Hawaii site.

At the Puerto Rico site, the seawater pipes would be installed in trenches running parallel to the sea's surface because of the shallow water in the near-shore zone.

10-MWe POWER PLANT LAYOUT

The general layout of a 10 MWe power plant is shown in Figure V-8. The layout is basically the same as for the 40 MWe configuration, but on a smaller scale. The power module is situated between the warm and cold seawater troughs with designated areas behind the OTEC plant for general maintenance and storage, nitrogen and ammonia storage, a power sub-station, office, parking, and an access road.

A more detailed plan view of the 10 MWe power plant is presented in Figure V-9 showing the seawater pipes, the pumps and heat exchangers, and the major components of the power module. The arrangement of components is identical to the power module used in the 40 MWe plant, as shown in Figures V-3 and V-4. A side elevation of the 10 MWe plant in Figure V-10 shows the single seawater pump submerged in the warm water intake plenum, and the warm water discharge pipe in its slanted trench. This arrangement, again, is representative of the Keahole Point installation.

Figure V-6. End Elevation, 10 MWe Power Module

Figure V-7. Side Elevation, 40 MWe Power Plant

Figure V-8. 10 MWe Power Plant Layout

Figure V-9. Plan View, 10 MWe Power Plant

Figure V-10. Elevation, 10 MWe Power Plant

ALTERNATE POWER PLANT CONFIGURATIONS

Early in the course of this conceptual design study, one of the critical technical issues to be resolved was the location of the power modules relative to sea level. The issue was whether the power modules, in particular the heat exchangers, could be located on the beach above sea level, or whether they had to be located below sea level in a deeply excavated area on the shore. Given the fact that the tops of the heat exchangers would be open to atmospheric pressure, it became evident that they and the seawater pumps would have to be installed at or below sea level in order to avoid large pumping losses in the seawater system.

The significance of locating the heat exchangers below sea level is illustrated in the following example: The water flow rate through the evaporator of a 10 MWe power module is 273,500,000 pounds per hour. The seawater flow rate through the condenser is 252,600,000 pounds per hour for a combined seawater flow of 526,100,000 pounds per hour. If this amount of water were pumped one foot above sea level, the power required would be 526,100,000 foot-pounds per hour or 198.22 KW. $(526,100,000 \text{ ft-lb/hr} \div 3600 \text{ sec/hr} \div 550 \text{ ft-lb/sec/hp} \times 0.746 \text{ KW/hp} = 198.22 \text{ KW})$. If the heat exchangers were located above ground at the Keahole Point site with their open tops roughly 50 feet above sea level, the seawater pumping losses would total 9.91 MW, and a nominal 10 MWe power module would become a 0.09 MWe power module!

Since it was obvious that the heat exchangers would have to be located below sea level, the power plant configurations depicted in Figures V-11 through V-14 were originally developed for both candidate sites. Figure V-11 shows an end elevation of a 10 MWe power module which is typical of a 10 or 40 MWe power plant. The seawater pumps and heat exchangers are located in separate plenums or troughs which would be excavated to a depth of about 50 feet below sea level. This is identical

Figure V-11. Elevation, 10 MWe Power Module

to the arrangement of pumps and heat exchangers shown previously in Figure V-3. The power producing, ammonia cycle components of this module, however, are shown below ground, located in a two-level excavated area between the seawater troughs. This arrangement allows for the most direct possible routing of ammonia vapor piping from evaporator to turbine to condenser. It also effectively locates all of the components in the liquid ammonia loop below the level of liquid ammonia in the heat exchangers. An overall plan view of the original 10 MWe power module is shown in Figure V-12, and a plan view of the liquid ammonia loop components of the lower level is shown in Figure V-13. The original configuration of a 40 MWe power plant is shown in plan view in Figure V-14.

The original configurations of the 10 and 40 MWe power plants were described in a presentation to representatives of the DOE at Value Engineering on August 21, 1978. Since that time, however, members of the DOT/Value Engineering team have visited the proposed plant sites in Hawaii and Puerto Rico and met with knowledgeable representatives of the construction industries in both areas. As a result of these site visits, it became evident that construction of a land-based OTEC plant as originally conceived would be unnecessarily costly and difficult. In particular, at the Keahole Point site in Hawaii, excavation of the hard lava rock would require continuous drilling and blasting operations to a depth of approximately 66 feet below the existing ground level. This type of excavating operation would result in a cost of roughly \$70 per cubic yard simply to dig a hole for the power modules. Moreover, the lava rock formations at the site are so porous that it is virtually impossible to keep an excavated hole dry once it is dug to below sea level. This would add further cost and complexity to the construction effort, particularly in the case of the central excavated area which must be kept dry to house the ammonia loop components.

Figure V-12. Plan View, 10 MWe Power Plant

Figure V-1 Plan View, 10 MWe Power Module Lower Level

Figure V-14. Plan View, 40 MWe Power Plant

The original conceptual design of the power plant was consequently modified to help reduce the cost of construction. The central excavated area between the seawater troughs was done away with, and the ammonia loop components were rearranged so that most of them could be installed at ground level between the troughs, as shown in Figures V-5 and V-6. The seawater plenums remained virtually the same, with the exception that the evaporator and condenser sumps would now be installed in the seawater plenums to insure that they would remain below the operating level of liquid ammonia in the heat exchangers. The ammonia feed pumps would now have to draw the condensed ammonia up out of the submerged sump tanks, but initial calculations of static head loss and pump inlet pressure requirements indicate that this condition should not significantly affect power cycle performance. If further detailed study of the ammonia cycle indicates that the feed pumps must be placed at or below sump level, then they could be installed in separate, dry sumps submerged in the seawater troughs, although this would somewhat hinder access to and maintenance of the pumps. Figure V-15 graphically illustrates the savings in construction costs which can be realized for a 40 MWe plant in Hawaii.

Geological information on the proposed site at Punta Yeguas, Puerto Rico is not as complete as the information available for Hawaii. Preliminary estimates on the cost of excavation in the Punta Tuna area indicate that the cost per cubic yard of excavated material will be much lower than for Hawaii, at least for relatively shallow digging or dredging. However, there is not enough data available at this time regarding deep excavations to enable an accurate comparison between the original power plant configuration and the modified configuration. For the purposes of cost comparison in this study, the modified plant configuration has been adopted for both Hawaii and Puerto Rico in order to minimize the number of differences between the two plants.

2460A

Original Plan: 97,000 Cu Yds @ \$70/Cu Yd = \$6.79M

Modified Plan: 65,000 Cu Yds @ \$70/Cu Yd = \$4.55M
Savings of 2.24M

Figure V-15. 40 MWe Power Plant Site Excavation

SECTION VI

SEA WATER PIPES SYSTEM

The sea water pipes system presented in this section are those conduits required to take in and discharge both the cold and warm sea water required for OTEC plant operation. The major emphasis is on the cold water intake pipe, because it is the longest line and is in the deepest water. The discharge line for the cold water is the second longest line. The warm water side consists of an intake channel and a relatively short pipe line for warm water discharge.

Design and installation of the cold water intake line presented the most challenging engineering aspect of this conceptual design study. The large diameter requirements and the depth of water for installation both exceed the demonstrated capabilities of the offshore pipe laying industry. However, the pipe design and installation methods presented here are deemed to be workable, involving the minimum extension of existing technologies. Since the offshore seafloor conditions are quite different for the two sites studied, two different designs and installation methods are presented. A description of the current state of the art relative to the offshore petroleum industry is included in the working papers associated with this report.

PIPE MATERIALS SELECTION

Figures VI-1 and VI-2 show the required pipeline lengths and diameters for the two locations. The pipeline lengths were chosen to meet the following criteria.

- The cold water intake is to be located at a water depth of 3000 feet to assure a minimum temperature differential of 20° C throughout the year.
- The warm water intake location is selected to minimize coastal current and surge effects.

Figure VI-1. Comparison of Seawater Pipe Lengths

Figure VI-2. Concrete Pipe Size Comparisons

- The cold-water and warm-water discharge depths are to consider the potential for thermal mixing and possible biofouling.
- The pipeline routes are to be located in accordance with the seafloor profile considerations presented in Section IV.
- The pipeline lengths are to be the minimum compatible with deployment methods, pipe design, and on-land plant siting.

In view of the increased pipeline length, when compared to a floating platform-based OTEC plant, and the associated increased flow losses, it was decided to "normalize" the pipe diameters for a given net power output rather than increase the pumping power. Thus, for example, a nominal 15-foot I.D. pipe for a 10 MW_e floating plant was increased to a 22-foot I.D. pipe for Hawaii and a 25-foot I.D. pipe for Puerto Rico. Further, the pipes are trenched and buried for surf zone protection to a water depth of about 100 feet.

A selection of pipe design and material must be made in conjunction with considering the installation method and the resulting pipe stresses. The most fundamental categorization of possible installation methods depends on whether the pipe should be light (buoyant) or heavy (resting on the seafloor). Thus the candidate pipe materials were grouped in these two categories. Table VI-1 presents a list of candidate pipe materials and the estimated cost for manufacturing a 5800-foot length of pipe for the two plant sizes. This comparison is for the deep water, steeply sloped, portion of the cold water intake pipe only because in the shallow water zones the pipe will be trenched and buried, eliminating any advantages of buoyant pipes. Furthermore, the selection of pipe materials for the shallow water zones can be based primarily on cost comparisons since industry has closely related construction and installation experience for nuclear plant cooling water and large sewer outfalls.

Table VI-1. Comparative Costs for Cold Water Pipe Materials

Candidate Materials		Data Source	MANUFACTURED COST (\$1000)			
			10-MW Plant 22 to 25-ft Diameter		40-MW Plant 30 to 33-Ft. Diameter	
			\$/Lin Ft	Total \$	\$/Lin Ft.	Total \$
Heavy	Concrete	Ameron Kaiser/Fluor	1.667	9,670	2.583	14,981
	Steel		3.505	20,330	5.874	34,070
Buoyant	Fiberglass Reinforced Plastic	Fiberglass Structural Engineering	2.640	15,320	4.004	23,230
	Rubber Coated Nylon	Goodyear	6.56	38,050	8.941	51,860

In addition to the four materials examined (concrete, steel, FRP, and rubber-coated nylon) several other materials have been suggested for floating OTEC plant cold water pipes. These include: polyvinyl chloride (PVC), corrugated metal culvert, and composite steel and concrete pipe. These materials were eliminated from further investigation early in the study because a cursory examination of costs, manufacturing problems, and long term exposure to sea conditions did not indicate any obvious advantages over the four candidates selected for investigation.

Concrete Pipe - The data developed for concrete pipe is based on information supplied by the Ameron Corporation. This company has extensive experience in the design and manufacture of large concrete pipes used for water transport projects, nuclear power plant cooling water, and sewer outfalls. Their current projects include:

- Manufacture of 18-foot diameter concrete pipe for offshore installation to supply cooling water for the San Onofre nuclear plant in Southern California (see Figure VI-3).
- Manufacture of 21-foot inside diameter pipe for the central Arizona water project (see Figure VI-4).
- Proposal for the manufacture of 28-foot diameter concrete pipe for Bureau of Reclamation in Washington State.

The pipe manufacturing process calls for setting up a plant at the job site. Pipe sections approximately 25 feet high are cast with reinforcing steel in vertically oriented forms. These sections are then prestressed with an outer helical wire wrap and coated with mortar. They are then transferred to the launch facility using a "pipe-mobile" (Figure VI-5) where four 25-foot sections are post-tensioned together with spherical-joint end pieces to form 100-foot-long sections for installation. The cost estimates shown in Table VI-1 are based on pipes having the following dimensions:

Figure VI-3. 18-Ft Pipe Fabrication Plant, San Onofre

Figure VI-4. 21-Ft Pipe, Arizona Water Project

Figure VI-5. Pipe-Mobile and Concrete Pipe
VI-9

	<u>10 MW</u>	<u>40 MW</u>
Pipe inside diameter	22 feet	30 feet
Pipe outside diameter	24 ¼ feet	33 feet
Weight/foot in air	12,200 lbs	23,000 lbs

A proportionate share of the plant mobilization cost is included in the cost estimate. Manufactured cost includes all pipe materials, labor, plant mobilization and set-up to provide post-tensioned 100-foot-long sections located on the launchways. It does not include the cost of the site for the plant.

Reinforced concrete has excellent durability in a seawater environment. With proper quality control, protection of reinforcing steel, and final detailing, it is capable of withstanding the action of seawater for 25 years or more.

As shown in Table VI-1 it has the lowest manufactured cost of the candidate materials. The primary disadvantage of concrete pipe is its weight, even for the proposed lighter weight concrete. The large pipe weight necessitates additional costs in the installation operations and the required structural support on the seafloor.

Steel Pipe. The data developed for steel pipe is based on information supplied by Kaiser Steel Corporation combined with Fluor Corporation's pipeline experience. The cost estimates are for A-36 steel, rolled and seam-welded pipe manufactured in an existing plant. The completed sections are then shipped to the construction site. The pipe estimated has the following estimated properties:

	<u>10 MW</u>	<u>40 MW</u>
Pipe inside diameter	22 feet	30 feet
Weight/Foot in air TOTAL	3120 lbs.	5420 lbs.
Steel wt.	2340	4360
Coating wt.	780	1060

In addition a cost allowance for internal and external coatings is included.

Steel pipe is susceptible to corrosion in seawater. The steel pipelines maintained in the ocean are usually coated with several inches of concrete or grout to prevent seawater corrosion

3. Fiberglass Reinforced Plastic (FRP). The data developed for FRP pipe was based on a conceptual study conducted by the Fiberglass Structural Engineering Company. Their report is included in the working papers. This company has extensive experience in the design and manufacturing supervision of large diameter FRP pipe. Their recent projects include:

- Design and supervision for a 24-foot diameter, 1215-foot-long FRP chimney liner (See Figure VI-6).
- Design and supervision for a 32-foot-diameter cross-flow scrubber, 80 feet long. (See Figure VI-7).

The report provides conceptual designs and rough cost estimates for two diameters of cold water pipe each 5000 feet long. For comparison purposes this cost estimate was adjusted to the 5800-foot length basis for Table VI-1 data. The pipe designed and estimated has the following dimensions:

	<u>10 MW</u>	<u>40 MW</u>
Inside Diameter	25 feet	33 feet
Maximum Wall Thickness	4.2"	4.2"
Minimum Wall Thickness	1 1/2"	1 1/2"
Approximate Buoyancy Range	20 to 160 lbs/ft	26 to 235 lbs/ft

Figure VI-6. 24-Ft FRP Pipe Chimney Liner

Figure VI-7. 32-Ft FRP Pipe Scrubber Tower
VI-13

The estimate is based on setting up a pipe fabricating facility on the south coast of Puerto Rico. Equipment and pipe material would be shipped to the fabrication site. Here two winders with mandrels capable of producing 60-foot pipe segments would be set up. The pipe would be filament wound with multiple helix angles. Between the inner and outer FRP walls, a light weight filler would be sandwiched. The filler would be balsa wood in the shallower water portions and syntactic foam for higher hydrostatic pressure requirements in the deeper water. Primarily because of differential pressure the shallower pipe sections would have a 4.2-inch-thick wall (1 inch outer FRP wall, 2.2 inch filler, and 1 inch inner FRP wall). Near the deep intake end this would reduce to a 1-1/2 inch-thick wall (3/8 inch outer FRP, 3/4 inch filler, and 3/8 inch inner FRP). In addition, the pipe would include FRP ring stiffeners which also serve as ballast chambers. The 60-foot pipe length would be joined at the beach front into 833-foot lengths using interior and exterior FRP overlays. The ends of the 833-foot length would have FRP flanges overlayed in place. The flanged pipe would be launched and moored in a bay. These sections would subsequently be bolted together using corrosion resistant titanium bolts. Thus a single long length of pipe would be ready for tow-out and installation.

The primary advantages of the FRP pipe are its lightweight and its good corrosion resistance. Its primary disadvantage is its high cost compared to concrete.

4. Rubber-Coated Nylon (RCN). The data developed for rubber-coated nylon was based on information supplied by Goodyear Aerospace Corporation. Though there appear to be no previous applications of this material to this type of problem, Goodyear offered order-of-magnitude cost estimates and some design suggestions.

The proposed RCN pipe design has the following dimensions:

	<u>40 MW</u>
Pipe inside diameter	30 feet
Wall thickness	~1 inch
Materials	Rubber, fabric, nitrile, neoprene, stainless steel, syntactic foam
Weight per foot in air	1,050 lbs/ft

The pipe is made of 8-foot wide, compliant fabric/metal segments fabricated on conveyor belt building equipment. The sections are spliced to form a cylinder. The tensile load is carried by cables molded between a rubber liner and rubber cover. The cables attach to stiffening rings, spaced between pipe sections. The rings and belting material would be shipped to the job site. There they would be spliced together using a proven cementing technique. The stiffening ring sections would be welded together and attached at each end of an approximately 40-foot-long pipe section. Syntactic foam would be added to provide buoyancy. Additional information on this manufacturing process appears in the project working papers.

Further investigation of this pipe material was discontinued because of its relatively high cost.

Among the four candidate pipe materials investigated, the one selected for use at the Hawaii site was based on: (1) least cost for manufacture and installation, (2) greatest resistance to long-term effects of sea water and (3) existence of demonstrated related industry experience. Concrete pipe best satisfied these criteria.

For the Puerto Rico site, FPD was selected for the deep water portion of the cold water intake pipe after evaluating the extreme irregularities apparently present along the seafloor pipeline route.

in deep water. (See Section IV). These irregularities precluded the use of a pipe resting on the seafloor. It was felt that concrete pipe could not be designed to span distances between rock outcroppings nor could the pipeline route in these water depths be economically prepared to support the pipe. Concrete pipe was, however, selected again for those lengths of pipe in water shallow enough to be dredged and smoothed.

In selecting the best methods to install the cold water pipe in the deep water, steep slope zone, several methods were defined in categories and partially developed conceptually. Figure VI-8 categorizes a wide range of possible installation techniques. They are first divided with respect to whether the pipe is installed in a single length or multiple sections. The next level further divides these as to whether the pipe is transported to its final position along the seafloor or on the surface. The final division relates to whether the pipe deployment proceeds toward the deeper water or toward the shallow water. Defining the installation options in this manner provides some assurance that all possibilities are being considered. Figures VI-9 and VI-10 illustrate the 6 installation methods thus defined.

These installation methods were evaluated together with pipe material and site preparation considerations using a subjective Cost/Technical Risk Factor as shown in figures VI-11 and VI-12. On this basis, Method 4 (Multiple Sections, bottom pull-out, up-slope laying) was selected for the concrete pipe sections for the Hawaii Site, while Method 3 (single length, surface pull-out, shallow water start) was selected for the FRP pipe for Puerto Rico. These methods are more fully described later in this section.

Figure VI-8. Category Definition, Pipe Installation

METHOD 1

Single Length
Bottom Slope Pull-Out
Shallow Water Start

METHOD 2

Single Length
Surface Pull-Out
Deep Water Start

METHOD 3

Single Length
Surface Pull-Out
Shallow Water Start

Figure VI-9. Single Length Pipe Installation Methods

METHOD 4

Multiple Sections
Bottom Slope Pull-Out
Up-Slope Laying

METHOD 5

Multiple Sections
Surface Tow-Out
Up-Slope Laying

METHOD 6

Multiple Sections
Surface Tow-Out
Down-Slope Laying

Figure VI-10. Multiple Pipe Sections Installation Methods

Single Length
Bottom Pull-Out
Shallow Water Start

Cost/Tech Risk Factor
 $(0.025 + 0.95 + 0.15)0.7 = 0.79$

Single Length
Surface Pull-Out
Deep Water Start

Cost/Tech Risk Factor
 $(0.025 + 0.95 + 0.18)0.5 = 0.58$

Single Length
Surface Pull-Out
Shallow Water Start

Cost/Tech Risk Factor
 $(0.025 + 0.95 + 0.15)0.6 = 0.68$

Figure VI-11.

Cost/Tech Risk Factors for Buoyant Cold Water Pipe,
Deep Water Zone, 40 MWe, Off Hawaii

Multiple Sections
Bottom Pull-Out
Up-Slope Laying

$$\text{Cost/Tech Risk Factor} \\ (0.08 + 0.16 + 0.3)0.3 = 0.16$$

Multiple Sections
Surface Tow-Out
Down-Slope Laying

$$\text{Cost/Tech Risk Factor} \\ (0.08 + 0.16 + 0.28)0.5 = 0.26$$

Multiple Sections
Surface Pull-Out
Up-Slope Laying

$$\text{Cost/Tech Risk Factor} \\ (0.08 + 0.16 + 0.28)0.4 = 0.21$$

Figure VI-12. Cost/Tech Risk Factors for Heavy Cold Water Pipe,
Deep Water Zone, 40 MWe, Off Hawaii

B. SEAWATER PIPE SYSTEMS DESIGN AND INSTALLATION

The pipe materials selected for the two OTEC plant sites and the required pipeline and trenching lengths are tabulated below:

	<u>Hawaii</u>	<u>Puerto Rico</u>
<u>Cold Water Intake</u>		
Shore Zone		
Pipe Material	Concrete	Concrete
Pipe Length	2400 ft	5200 ft
Trench Length	620 ft	4500 ft
Deep Zone		
Pipe Material	Concrete	FRP
Pipe Length	5800 ft	5300 ft
<u>Cold Water Discharge</u>		
Pipe Material	Concrete	Concrete/FRP
Pipe Length	2500 ft	5600 ft (incl 400' FRP)
Trench Length	620 ft	4500 ft
<u>Warm Water Discharge</u>		
Pipe Material	Concrete	Concrete
Pipe Length	1200 ft	5200 ft
Trench Length	460 ft	4500 ft

The same data is also presented graphically in Figure VI-1.

These data evolved as the result of obtaining more specific bathymetry charts and selecting more specific plant locations. As discussed in Section IV, the specific Hawaii plant location is approximately 200 yards south of the Keahole Point lighthouse, while the Puerto Rico plant site is at the head of a small cove adjacent to Punta Yeguas approximately 3 miles east of Punta Tuna.

Selection of specific plant sites and pipeline routes allowed the designs and cost estimates to be refined. Even though new information may cause other specific locations to be selected, these design assumptions are generally applicable to the areas being considered.

Since pipe design and installation method are closely inter-related, they are presented together. Since the Hawaiian and Puerto Rican OTEC plant locations present quite different design problems, their design and installation methods are presented separately.

Hawaiian Location-Sea Water Pipe Design and Installation

In preparation for detailed pipe design and installation planning, a detailed survey of seafloor conditions must first be made. The offshore data base for the pipeline design and installation method described herein consists of the following:

- 1) Final Report - The Meteorological and Oceanographic Conditions for Two Land-Based OTEC Sites prepared by Evans-Hamilton, Inc. 20 September 1978.
- 2) An offshore bathymetric contour map prepared by the University of Hawaii. This chart shows subsea contours plotted on 50-foot intervals.
- 3) Color film taken along a proposed pipeline route from the Star II submersible by Dr. Ed Noda. The maximum water depth observed was 1400 feet.
- 4) A visit to the Keahole Point site and discussions with engineers involved in the Mini-OTEC program and the Seacoast Test Facility.
- 5) The Environmental Impact statement prepared for the Natural Energy Laboratory of Hawaii, Phase I.

The engineering design conclusions drawn from this data base are:

- 1) The average seafloor slope beyond the 500-foot water depth is 26° .
- 2) The deep water slope is a very smooth, uniform lava flow.
- 3) The seafloor material is dense, hard basalt.
- 4) Some rock outcrops exist around the 500-foot water depth. A favorable pipeline route, requiring minimal rock removal, can be selected through this zone.
- 5) The seafloor is fairly uniform from the 500-foot to 60-foot water depth with some loose boulders that will need to be removed.

These conclusions will need to be tested against data derived from a more detailed site survey. A section view of the proposed Cold Water Intake pipeline route is repeated as Figure VI-13.

The following describes a method for installing the selected concrete pipe that is deemed to be workable, involving the minimum extension of existing technologies. It is not the least costly method investigated; however, it does appear to contain the least amount of risk, relying on existing techniques in the manufacture of large diameter concrete pipe and deep water exploratory drilling.

An essential, costly element of this pipeline installation method is a dynamically positioned (DP) drillship. The steep slope, deep water, and hard seafloor would preclude using a conventionally anchored vessel. The DP drill ship will be used to establish the deepwater termination of the Cold Water intake pipe by drilling and cementing a structure to the seafloor that will resist downslope loads imposed by the heavy pipe sections.

While concrete pipe sections are being constructed onshore, the DP vessel would be mobilized. It would proceed to the site where a steel

Figure VI-13. Bottom Profile A, Keahole Point, Hawaii
VI-25

tubular template (see Figure VI-14) would be "keel-hauled" and supported below the vessel. The DP vessel would proceed to the Cold Water Intake location where a single pilot bit and hole opener assembly would be run through the deadman template. A hole approximately 28 inches in diameter would be drilled 50- to 100- feet deep. (See Figure VI-15). A 24-inch O.D. by 18-inch I.D. piling would be run and cemented into the seafloor. (See Figure VI-16) The template would then be lowered to the seafloor, guided on the drill string, and slid over the piling gimbal base to secure its position. Two additional corner piles would be drilled and cemented to secure the template. Wire rope guidelines previously attached to the template would then be payed out to shore by an auxiliary workboat. A wire rope pull-in line, previously rigged around a sheave in the template, would also be transported to shore. The guidelines and pull-in lines would then be secured to winches mounted on shore front foundations. The DP vessel would then continue using the deadman template to drill and cement additional pilings in the template. The number, size, and depth of these pilings would depend on detailed knowledge of the engineering properties of the seafloor. Their function is to restrain the gravity load imposed by the heavy concrete pipe sections layed on the average 26° slope.

At the same time that the drilling and cementing of piling operations are being carried out, sections of concrete pipe will be transported from the fabrication area to the shore front launching facilities. There the sections will be joined, sealed, and post-tensioned together on launch ways to form sections approximately 100 feet long. (See Figure VI-17).

Each 100-foot section will contain a bell-and-spigot type end connection, pipe supporting feet, and guideline tubes. (See Figure VI-18). Two parallel launch ways, located in the excavations for the CWP intake and discharge troughs of the power plant, are planned so that offshore pipe installation may proceed continuously. This will minimize the expense of the offshore installation vessels.

Figure VI-14. Deadman Template, Cold Water Intake
VI-27

Figure VI-15. Drilling for Pile Section

Figure VI-16. Lowering Pile Section

Figure VI-17. Pipe Section Post-Tensioning and Launch Facility

Figure VI-18. Typical Concrete Pipe Section

VI-31

Once the 100-foot pipe sections are ready for installation, they will be maneuvered down the launch ways until sufficiently submerged to attach an installation buoyancy module. This module attaches to the pipe sections via "belly bands". (See Figure VI-19). This method assures minimum stress in the pipe sections thus enabling reduction in pipe weight, wall thickness, and cost.

The buoyancy module will have compartmented, remotely controlled buoyancy chambers, a TV system, and remote detachment capabilities. It will initially contain sufficient buoyancy to give the pipe section/buoyancy module combination near neutral buoyancy (slight positive buoyancy). The guidelines previously installed from the deadman template to the shore will be placed in guide tubes positioned on the sides of the pipe section. The pull-in lines will be run inside the pipe section. One of the lines will be secured to the aft end of the pipe section through a special strongback fixture. A wire rope sling will be secured from the top of the buoyancy module to a surface transport ship. An umbilical from the buoyancy module will also be run to the transport ship to control a stereo TV system (pan, tilt, and lights), and the remote buoyancy module actuation systems.

The first joint of pipe to be run will contain fixtures to secure it in the deadman template and an intake screen (if required). This section and subsequent pipe sections will proceed off the launch ways and down the pipeline route guided by the wire rope guidelines. See Figure VI-20. The sling attached to the transport vessel may normally remain slack. The slight positive buoyancy of the pipe/module section will be counteracted by the tension in the guide cables. Thus, vessel motion is normally decoupled from the pipe section. Should it be necessary, the elevation of the pipe section above the seafloor may be controlled either by varying the tension in the guide cables, or picking up tension in the sling attached to the transport vessel. Landing of the first special

Figure VI-19. Pipe Section Remote Installation Technique
VI-33

Figure VI-20. Transporting First Pipe Section

section of the pipeline in the template will be assisted by the DP vessel on location. Once sufficient pilings have been drilled and cemented, the DP vessel will be released in order to minimize cost. The DP vessel will, however, be used to drill and cement the shallower water cold water discharge and warm water discharge deadman before being released from the project.

As the bell and spigot joints are guided close to engagement by the guidelines, tension will be increased in the pull line. Through the strongback fixture at the shoreward end of the pipe this tension will act to pull the pipe sections into firm engagement. The connection is not designed to be pressure-tight; however, it will accommodate some axial misalignment and remain water-tight. A heavy mastic material will be applied to the bell surface prior to launch.

This installation technique will be repeated for each section.

After all the pipeline sections are in place, the guidelines will be tensioned and left in place to provide additional lateral stability. The deadman end of the guidelines will attach to buoyancy cannisters that will pull tight against a conical receiver on the template. This will allow the wire ropes to be inspected or replaced periodically by releasing the tension allowing the buoy to surface and be recovered.

The clothes line (pull line) assembly will remain in place allowing subsequent attachment of fixtures to inspect or maintain the inside of the pipe. These would be pulled along inside the pipe and then retrieved.

The final sections of pipe would be layed along the launch ways and run into the onshore OTEC plant. The near shore pipeline trenches will be backfilled with native rock to protect the pipe from surf action. The same procedure will be used for the cold water intake, the cold water discharge and the warm water discharge pipelines.

The 22-foot and 30-foot internal diameter concrete pipes designed are similar in construction to those currently being manufactured by Ameron for the San Onofre Nuclear Power Plant (18-foot I.D.) and the Central Arizona Water Project (21-foot I.D.). They are pre-cast reinforced, pre-stressed cyclindrical sections manufactured in 25-foot lengths. After four sections have been post-tensioned into 100-foot long sections, they are capable of safely supporting their own weight when simply supported at each end. The sections are first case and cured in vertical steel forms containing internal reinforcing steel bar. Next they are transported to a pre-stressing facility that wraps the O.D. of the section with steel wire under tension by spinning the pipe section. The same facility applies an external mortar coat to protect the pre-stress wire from sea water corrosion. These sections are stored until needed for post-tensioning on the launch ways.

The required dimensions are resulting weights for the two pipe sizes are:

are:

	Plant Size	
	10 MW	40 MW
Pipe Inside Diameter (ft)	22	30
Total Wall Thickness (in)	13.2	18
Weight per foot in air	12,200	23,000
Weight per foot in sea water	7,100	13,500
Est. Cost/Lin. Ft. (\$1978)	\$1,000	\$ 1,750
Est. Mobilization cost		
	(\$1978) \$8 million	\$10 million

The cost estimates include all materials, labor, and supervision to manufacture the 25-foot long sections, position them on the launch ways, and post-tension them together. The mobilization cost includes furnishing and installing all the specialized manufacturing and handling equipment and related facilities on a site provided by others adjacent to the OTEC plant site.

Puerto Rico Location - Sea Water Pipe Design and Installation

In preparation for detailed pipe design and installation planning, a detailed survey of the seafloor conditions must first be made. The offshore data base for the pipeline design and installation method described herein consist of the following:

- 1) Final Report - The Meteorological and Oceanographic Conditions for Two Land-based OTEC Sites prepared by Evans-Hamilton, Inc.
- 2) Hydrographic Survey "Boat Sheets", No. 9607 and 9608 prepared by the National Ocean Survey in 1976. These show specific soundings to water depths of only 1500 feet.
- 3) Visit to the Punta Tuna area and discussions with engineers involved in offshore pipeline construction and installation.
- 4) Discussions with Dr. Sasscer and Dr. Goldman of the Center for Energy and Environmental Research, Mayaguez, Puerto Rico.
- 5) Discussions with Puerto Rico Water Resources Authority.
- 6) Report-Preliminary Conceptual Design for PROTEC by Black and Veatch, 1978.

The engineering design conclusions/assumptions drawn from this data base are:

- 1) The average seafloor slope beyond the 300-foot water depth is 45° with some portions averaging 65° .
- 2) The deep water slope is extremely irregular with frequent large rock outcrops.
- 3) From the shoreline out approximately 5,000 feet, the water depth is generally less than 60 feet. The seafloor material is a mixture of coral sand and silt capable of being dredged, mixed with firm dense rock.

There appears to be no detailed bathymetric or geologic data available for water depths greater than 1500 feet for this specific area, so some conclusions were inferred from verbal descriptions of deep water located as far away as St. Croix. Thus these conclusions will need to be tested against data derived from a more detailed site survey. A section view of the proposed cold water intake pipeline route is repeated as Figure VI-21. The following describes a method for installing both the selected buoyant FRP deepwater pipe section and the near shore concrete pipes. The buoyant pipe method is deemed workable, but will require some development and testing prior to committing to its construction. The shallow water design and installation method are within the state-of-the-art of concrete pipe.

Prior to manufacturing the buoyant FRP pipe, a detailed investigation and selection of a cold water intake pipeline route will be made. It is necessary to locate approximately six deadweight anchor locations at approximate equal spacing along a straight line. To accomplish this both a research surface vessel and a submersible of the Deep Quest type will be used. The anchor locations are shown in profile in Figure VI-22. The route will also need to be selected so that rock outcrops will not interfere with the pipe when it is held 50 to 100 feet above the seafloor. The anchor points will be marked with sonic transponders and their location accurately surveyed. These data will determine the specific lengths of pipe to be fabricated.

The six deadweight anchors will be deployed as shown in Figure VI-23. A 150-ton derrick barge outfitted with lowering winches will be mobilized. It will be positioned sequentially over each anchor position. The concrete deadweight anchor will be lowered on a two-part line and landed at the transponder location. Its position will be monitored and confirmed by the submersible. The two ends of the lowering line will be supported on the surface by a buoy. With the six systems installed, the derrick barge will be brought back to shore

Figure VI-21. Bottom Profile, Punta Yeguas, Puerto Rico
VI-40

Figure VI-22. Bottom Profile Showing Approximate Locations of Deadweight Anchors
VI-41

Figure VI-23. Deadweight Anchor Deployment Method

to stand by for the arrival of the FRP pipe.

The 5300-foot length of FRP pipe would be made up of six pipe sub-assemblies joined by flanged and bolted connections. Figures VI-24, VI-25, VI-26, and VI-27 show typical fabrication detail. The flanged connections also serve as the points where wire ropes will be attached to hold the buoyant pipe near the seafloor. Positive buoyancy is achieved using a low density, high compressive strength inner core. The amount of buoyancy would be adjusted by adding or subtracting a granular ballast material from a cavity in the ring stiffeners.

The pipe is filament-wound on 60-foot-long mandrels. Multiple helix angles are planned for both the inner and outer FRP walls in order to develop the specific strength required. Each stiffener ring will also be wound while the pipe segment is on the mandrel, making it an integral part of the pipe wall. The interior low density core will be fabricated between the inner and outer FRP laminate in a similar fashion.

The pipe would be fabricated using a premium Vinyl Ester Resin with high elongation and impact resistance. Both the interior and exterior laminates would use a chlorinated resin to prevent or reduce the accumulation of biofouling.

Buoyancy is obtained through the use of a low density sandwich core material between the inner and outer FRP laminates. The governing mode of pipe failure is buckling of the cylindrical shell due to the pressure differential resulting from flow inside the pipe. The sandwich core serves a second function in providing sufficient wall thickness to resist buckling pressure. At lesser depths, the core material would be balsa wood. At greater depths and larger hydrostatic pressure, a solid FRP laminate would be used with buoyancy provided by syntactic foam in the stiffener ribs. This preliminary design uses an FRP with a density of about 121 lbs/ft³ and a core material with a density of about 10 lbs/ft³. Typical pipe design dimensions are tabulated below.

Figure VI-24. Fabricated Spool with Alignment Bell and Butt Joint

Figure VI-25. FRP Pipe Wall Construction

Figure VI-26. FRP Flange and Joint Detail

Figure VI-27.. Anchor Assembly

BUOYANT PIPE WALL CONSTRUCTION

Diameter	Buoyancy	Total Wall Thickness	FRP Wall Thickness	Core Thickness
25' Ø	20 lb/ft	1.60"	.75"	.85"
25' Ø	20 lb/ft	2.10"	1.00"	1.10"
25' Ø	20 lb/ft	4.20"	2.00"	2.20"
25' Ø	160 lb/ft	3.85"	1.65"	2.20"
33' Ø	26 lb/ft	1.60"	.75"	.85"
33' Ø	26 lb/ft	2.10"	1.00"	1.10"
33' Ø	26 lb/ft	4.20"	2.00"	2.20"
33' Ø	235 lb/ft	4.00"	1.65"	2.20"

It is tentatively planned to set up the pipe fabricating facility on some undeveloped land adjacent to the Puerto Yabucoa tanker terminal bay, located three miles east of the Punta Yueguas site. By using two winders, three 8-hour shifts per day, and operating seven days per week, the full 5300-foot length could be fabricated in one year. This period could be reduced to six months by using four winders instead of two. Special pipe carriers are planned to extract each pipe segment from the mandrel, transport it to the assembly area, and maneuver the pipe segment for proper alignment during the joining process. These special vehicles will also be capable of weighing each pipe segment so that the correct amount of ballast can be calculated.

A wide, relatively flat length of sandy beach, tentatively located at the Puerto Yabucoa site, would be used for assembly of the 60-foot pipe lengths as they are delivered from the production site. Alignment bells on one end of each pipe segment will facilitate joining of the segment which would then be welded by interior and exterior secondary

overlays. As each length of pipe is completed, the support cradles on the side of the pipe facing the sea would be removed and the entire length allowed to roll into the water. These lengths of pipe would then be towed into a protected area where they could be safely moored until final assembly. Should bottom conditions or other considerations require that the pipe ride higher in the water, end domes could be attached before deployment, thus sealing the interior from flooding.

The final assembly of the six sub-assemblies would be accomplished relatively easily and quickly. The flanged ends of the sub-assemblies would be brought together and bolted on each side. With the pipe segment securely attached, the remaining bolts would then be installed. This could be done either by workmen operating from small boats or by a workman standing on top of the floating pipe. Should the first alternative be selected, rubber fenders should be used to protect the pipe wall, or should the latter alternative be chosen, a strip of "non-skid" should be applied to the pipe wall around the flange hubs to provide secure footing for the workmen.

The completed FRP pipe assembly would next be towed to the pipeline route area and be secured to one end of the buoy supported wire rope. Figures VI-28, VI-29, VI-30, and VI-31 show the installation sequence. The near shore end of the pipe would be pulled down and secured to the previously installed concrete pipe termination block. Next the buoys supporting the wire rope pull down lines would be pulled down to a position near the seafloor and the loose ends of the pull down lines re-secured to the FRP pipe at all stations except the intake end (Figure VI-29). The derrick barge would then pull the intake pipe end below the water surface. Since the pipe is quite stiff, the entire length of pipe would gradually be submerged, the pipe remaining in a relatively straight line. As the pipe proceeded downward, the intermediate support buoys would rise. They provide constant downward force on the pipe to alleviate bending stresses.

Figure VI-28. Buoyant FRP Pipe Installation, Step 1

Figure VI-29. Buoyant FRP Pipe Installation, Step 2

VI-51

Pull Down Intake End of
Pipe while Buoys Provide
Passive Distributed
Pull-Down Force.

Figure VI-30. Buoyant FRP Pipe Installation, Step 3

Secure Pipe in Final
Position.

Buoy Lines May be Sequentially
Pulled to Achieve Proper
Position for Actuating
Locking Gate.

Figure VI-31. Buoyant FRP Pipe Installation, Step 4

VI-53

caused by buoyancy (Figure VI-30). With the entire pipe submerged to its final location the buoys would surface (Figure VI-31). After securing the intake pipe in its submerged location, the derrick barge would proceed to the surfaced buoy locations and with the assistance of the submersible secure and lock the pull down rope slings and pipe in their final position. Figure VI-32 illustrates the locking gate for the wire rope pull down sling. The ring pins shown are easily accessible by the submersible. The gate is actuated by pulling pin # 1. The gate may be spring actuated. The small buoy shown is a back-up means to further pull on the gate if necessary. Pin # 2 would drop into place, locking the gate, or placed by the submersible. Pin # 3 may be pulled to reopen the gate if pin # 2 is removed. Figure VI-33 illustrates the final position of the cold water pipe intake. Finally the submersible would inspect the entire pipe to ensure its proper position.

In parallel with the FRP fabrication and installation, the concrete pipe required for the near shore end of the cold water intake, the cold water discharge, and the warm water discharge would be fabricated in 25-foot-long sections having the following dimensions:

Plant Size	10 MW	40 MW
Inside Pipe Diameter	25 feet	33 feet
Nominal Wall Thickness	15 inch	19.8 inch
Weight in Air	15,800 lbs/ft	27,700 lbs/ft
Weight in Sea Water	9,200 lbs/ft	16,200 lbs/ft
Fabrication Cost	\$1,275/ft	\$2,175/ft
Plant Mobilization	\$8,000,000	\$10,000,000

The fabricating technique would be the same as described for the Hawaii site. except that each 25-foot section would have a bell and spigot connection cast in place. (See Figure VI-34). Individual 25-foot sections, rather than 100-foot sections would be installed offshore in a manner currently being utilized by the industry.

Figure VI-32. Locking Gate Assembly, FRP Pipe

Figure VI-33. Cold Water Intake, FRP Pipe

Figure VI-34. Typical Concrete Pipe Section, Puerto Rico

Each 25-foot section would be transported by a "pipe mobile" from the fabrication yard and loaded on a barge. A specially equipped "jack-up" vessel would have previously been installed over the offshore pipe trench. A section of pipe (perhaps two sections) would arrive at the jack-up on the barge. A pipe section would be transferred to slings supported from the gantry crane on the jack-up. The pipe section would be submerged and maneuvered into connection with a previously installed pipe. The final connection may be assisted by the "Hydropull" technique. This uses a water tight pipe end bulkhead and hydraulic water pump to create a slight vacuum inside the pipe. The vacuum forces the bell and spigot connection into firm alignment to ensure water tightness. (This technique is being used effectively by Misiner Marine Construction for installing 12-foot diameter concrete pipe on the Southern Coast of Puerto Rico). This installation technique would be repeated until all pipeline sections for the three pipelines required are in place. The sections near the plant would be installed with the assistance of land cranes. A 400-foot FRP pipe section would be installed on the end of the concrete cold water discharge line where the seafloor begins to slope steeply.

The nearshore pipeline trenches would then be backfilled with native materials to protect the pipe from surfaction. The pipelines would be inspected and tested to assure water tightness.

VII. CONSTRUCTION AND INSTALLATION

Construction schedules for the four power plant options are presented in the foldouts of Figures VII-1 through VII-4.

In each case, the major tasks required for construction are identified and then divided into subtasks.

The bar chart shows the estimated time required for the completion of each subtask. The construction schedules do not include tasks such as site survey work, preparation of environmental impact reports, or acquisition of land and rights-of-way. It is assumed that these items will have been accomplished before actual site preparation is begun.

The construction schedules also do not include detail design or manufacture of the power plant components. It is assumed that the design and manufacture of all the required power plant components will have been accomplished in time for their delivery to the power plant site for installation.

40 MWe PLANT, HAWAII

As shown in Figure VII-1, the construction schedule for a 40 MWe OTEC power plant at Keahole Point, Hawaii encompasses a period of approximately 34 months from the initial mobilization of construction crews and equipment until completion of the power plant. At the end of this 34-month period, the power system should be fully functional, ready for start-up, initial testing, and generation of useful electric power. The construction phase is broken down into the following tasks:

Prepare construction sites

The construction sites consist of not only the power plant site itself, immediately adjacent to Keahole Point, but also staging areas, temporary storage yards, the concrete pipe fabrication area, and other areas which may be needed during the construction phase. Some of these areas may be situated up to several miles away from the actual power plant site, in locations which can be more easily cleared, graded, and

leveled than the rugged, lava rock terrain adjacent to Keahole Point. Approximately 40 acres of cleared and relatively level ground will be required for the concrete pipe fabrication yard and temporary pipe storage area. Several acres of ground will also have to be cleared and graded at the plant site itself to provide for equipment and raw materials storage areas. A portion of the cleared area at the power plant site will also be used for the final assembly, post-tensioning, and launching of the long lengths of concrete pipe.

As shown in Figure VII-1, the first subtask under construction site preparation is the construction and/or improvement of access roads. At the present time, there are no suitable access roads leading to the Keahole Point site, except a rough jeep trail. The Natural Energy Laboratory of Hawaii (NELH) plans to construct a light-duty road from State Highway 19 to Keahole Point to provide access to their planned Seacoast Test Facility (see Reference 11). This road may have to be further improved, however, during the construction phase of an OTEC power plant to enable its use by the extremely large vehicles which will be required to move the concrete pipe sections and large power plant components to the site.

The next step in preparation is to clear and grade the pipe fabrication site. This subtask can begin shortly after work on the access roads is begun, since the pipe fabrication yard most likely will be in an area closer to established roads. Utilities such as water supply, sewage, and electrical lines will then be installed at the fabrication area, and later at the power plant site. The fourth item is the installation of fences, area lighting, and temporary office buildings, storage sheds, etc. These first four subtasks will require approximately 11 months to complete.

Subtasks 1.5 and 1.6 include the detailed design, construction, and installation of all the equipment necessary for fabrication of the large diameter concrete pipe sections. It is estimated that approximately 15 months will be required from initial mobilization of the design effort until the first sections of concrete pipe can be manufactured on site. These two subtasks then become key pacing

items, since the pipe installation schedule is entirely dependent on how soon the pipe sections can be made available.

Subtask 1.7 shows the time required for actual pipe fabrication. Assuming that each section of pipe is roughly 30 feet long, and pipe can be manufactured at the rate of two to three sections per 8-hour working day, approximately 10 months will be required for pipe fabrication.

Develop plant site, Phase I

The actual development of the power plant site at Keahole Point has been divided into two phases. The first phase of site development involves preparations for assembling the concrete pipe sections into 100-foot lengths, post-tensioning each pipe assembly, and then positioning the pipe assembly for attachment of the buoyancy module. The first subtask is to excavate pipe launch ways. These are inclined troughs, approximately 80 feet wide, as shown in Figure VI-17, which later will be excavated further to become the intake and discharge plenums shown in the power plant layouts of Figures V-1 and V-7.

The next subtask in Phase I is to erect the pipe-handling equipment which will be necessary to position and support the individual pipe sections while they are joined, sealed, and post-tensioned. This equipment will consist of cradles and/or dollies to support the pipe, and rails or launch ways extending into the water to a depth at which the buoyancy module can be attached.

At the same time that the pipe handling and launching equipment is being installed, excavation can continue on the near-shore trenches in which the pipes will be buried. Because of the steeply sloped bottom contours at Keahole Point, these trenches will be relatively short (400 to 600 feet outward from shore). Since the area consists almost entirely of lava flows and basaltic rock, the excavations, both

onshore and offshore, will require drilling and blasting. It is estimated that phase I of plant site development will take up to 10 months.

Install cold water pipes

Several months before the completion of Phase I of plant site development, the vessels required for cold water pipe installation will be mobilized. Included among these vessels will be a DP drillship needed to drill and cement pilings for the cold water pipe termination template. Careful coordination of scheduling requirements will be needed at this point to minimize vessel costs, since a DP drillship may cost upwards of \$100,000 per day. At least one month's lead time will be required for mobilization of the various vessels needed for pipeline installation.

The first subtask of the DP drillship will be to install the cold water pipe intake template, as described in Section VI. As shown on the construction schedule, this job can be started well before the excavation of the near-shore trenches is completed, and should take no more than six or seven weeks.

Once the cold water pipe intake template is installed, the final pipeline route preparation can be carried out. This will involve a detailed visual survey of the proposed pipeline route, removal of any large boulders in the near-shore zone, careful routing of the guidelines through the rock outcropping area near the 500-foot depth contour, and routing of the pull line back to the winches and terminations on shore. The offshore termination for the cold water discharge pipe will also be installed by the DP vessel at this time. This termination will require only one or two pilings for location and support.

With careful planning, the final preparation of the pipeline route will be accomplished at the same time that the near-shore trenches are

completed. Installation of the deep water, steeply-sloped portion of the cold water intake pipe will then begin, following the procedure outlined in Section VI. This portion of the cold water pipe should take no more than five months to install.

The shallow water portions of the cold water intake and discharge pipes will be installed on less steeply-sloping contours in water depths less than 500 feet. The same basic installation technique will be used as for the deep water portion, starting at the seaward termination and installing pipe sections up the slope and into the near-shore trenches. This portion of the pipeline installation should require no more than 10 to 12 weeks.

After all the cold water pipe has been installed, it will require final inspection to insure that all the joints remain adequately sealed. Pipeline inspection can be carried out by a small, manned submersible or by a remotely controlled, unmanned vehicle equipped with closed circuit television. A screen will be installed at the deep water intake if further investigations of biofouling problems indicate that this will be necessary. Approximately two weeks are allocated for inspection and screen installation.

Backfilling and burying of the cold water pipes in the near-shore trenches is the final subtask in the pipeline installation procedure. This must be done in order to prevent damage to the pipes due to wave action in the shallow water zone near shore. Three to four weeks will be required to backfill and bury so that the pipe is completely covered to a water depth of about 50 feet.

Total installation time for the cold water pipes will be one year.

Install warm water pipe

Only a single warm water discharge line will be required for the land-based OTEC plant, because warm intake water will be pumped directly from near-shore surface waters via the open intake trough. Immediately after the DP drillship has completed installation of the deep water termination for the cold water pipe, it will be moved to a previously selected location where it will be used to install a termination block for the warm water discharge pipe. Final preparation of the pipeline route can be started shortly after the DP drillship begins installation of the termination block. As in the case of the cold water pipes, this will involve detailed visual inspection of the pipeline route, removal of any large boulders or obstructions, and rigging of guidelines and pull wires. Installation of the termination block will take three to four weeks, and pipeline route preparation no more than three weeks. The near-shore trench for the warm water discharge pipe will already have been excavated at this time.

Immediately after completing installation of the warm water discharge termination block, the DP drillship can be released from its duties and demobilized. Installation of the warm water concrete pipe sections cannot begin, however, until installation of the cold water pipes is completed. Once the cold water pipes are both completed, the vessels and buoyancy module used for concrete pipe installation will be moved over to the warm water pipeline route where installation operations can be started. Approximately three to four weeks will be required for installation, another week for inspection, and two to three weeks for backfilling and burying.

Develop plant site, Phase II

The first subtask in this final phase of power plant construction is to finish the excavation of the intake troughs and seawater plenums. Since these troughs are used initially for pipe assembly and launch ways, final excavation of these areas to the required depth cannot begin

until the pipelines are completed. It is estimated that 14 to 15 weeks will be required for this subtask, because the excavation will require careful rock drilling and blasting.

Shortly after the final seawater trough excavation is begun, work can be started on the installation of reinforced foundations, machinery mounting pads, walls, roof, and overhead cranes. The seawater troughs will also be lined with concrete to seal against water seepage through the porous lava rock. Approximately four months will be required for this subtask.

Installation of the actual power plant components can begin as soon as some of the foundations are completed. Assuming that all the heat exchangers, generators, turbines, pumps and other major components are already on site, the installation procedure should require no more than five months.

As soon as the components for one 10 MWe power module are installed, work can be started on the piping required for the liquid and gaseous ammonia loops. Plumbing and piping operations can proceed concurrently with installation of the remaining power plant components so that, although the piping subtask will involve 16 to 18 weeks, it will be finished only a month or so after all the components are installed.

In a similar fashion, the construction of the electric power substation and auxiliary equipment, such as installation of ammonia and nitrogen storage tanks, can be started well before the completion of the previous subtask. With careful planning, this final subtask can be accomplished in approximately three months to coincide with the completion of piping and plumbing. At this point, then, the 40 MWe OTEC power plant will be essentially complete, ready to be put into operation.

10 MWe PLANT, HAWAII

The outline of tasks and subtasks for construction of a 10 MWe OTEC power plant in Hawaii is identical to that for a 40 MWe plant. There are some items, however, which will require less time to complete because there are fewer components involved in the smaller power plant, the pipe size is smaller, and there is less excavating and site preparation required. As shown in Figure VII-2, the 10 MWe plant will require a total of approximately 30 months to complete, as compared to 34 months for the larger plant. The significant subtasks where time can be saved are as follows:

Prepare construction sites

It is estimated that subtasks 1.1 through 1.6 will require the same amount of time for the 10 MWe plant as for the 40 MWe size. The key items here are subtasks 1.5 and 1.6; the design, construction, and installation of concrete pipe fabrication equipment. It is felt that these subtasks will still require 15 months, because the machinery necessary for manufacture and handling of the 22-foot diameter concrete pipe will be virtually identical to that required for 30-foot diameter pipe. It is estimated, though, that two months' time can be saved during the actual fabrication of pipe sections since the pipe sections will be smaller, slightly easier to handle, and will require considerably smaller quantities of aggregate, cement, steel reinforcing bars, prestressing wire, etc.

Develop plant site, Phase I

Excavation of launch ways for the 22-foot diameter pipe will require approximately five months, compared to the six months required for the larger plant. An additional reduction of one month's time can be realized during the excavation of near shore trenches for the smaller diameter pipe. Subtask 2.2 will require the same amount of time as for the larger plant, however, resulting in a net saving.

of approximately two months during this first phase of plant site development.

Install cold water pipes

The first three subtasks under cold water pipe installation will require roughly the same amount of time as the larger diameter pipe. Some time may be saved during installation of the deep water termination template, owing to the fact that fewer pilings will be needed to support the weight of the smaller pipe. This will not significantly affect the overall timetable for pipe installation, however, because the DP drillship can remain on station to finish pile installation after the actual installation of pipe sections has begun. It is estimated that approximately one month can be cut from the deep water pipeline installation subtask, and another two weeks from the shallow water installation schedule. Inspection, screen installation, back-filling and burying of the near-shore pipes can be cut another week or so. The total difference in construction time for the two plant sizes in Hawaii up to this point would be approximately two and one-half months.

Install warm water pipes

The installation of the warm water discharge pipe for a 10 MWe plant would be carried out in exactly the same sequence as for the 40 MWe plant. Each of the subtasks in this operation will require approximately the same amount of time as the larger pipe size, and, consequently, very little time, if any, can be cut from the construction schedule for this item.

Develop plant site, phase II

Since only one power module will be installed in a 10 MWe plant, compared to four modules in a 40 MWe plant, each of the subtasks in the second phase of site development will result in some savings in

schedule time. Less material will need to be excavated for the seawater plenums, foundations and walls will be less extensive, fewer power plant components will be installed, piping will be simpler, and a smaller sub-station will be erected. It is estimated that the schedule for Phase II of plant site development can be reduced by six or seven weeks, bringing the total construction schedule for a 10 MWe OTEC power plant to 30 months.

40 MWe PLANT, PUERTO RICO

The construction schedule for a 40 MWe OTEC power plant in the Punta Tuna area of Puerto Rico is shown in Figure VII-3. The outlines of tasks involved for the Puerto Rico plants are different from the outlines for Hawaii for several reasons. First of all, two types of cold water pipe will be used; the shallow water portion consisting of conventional, pre-stressed concrete; and the deep water portion comprised of lightweight, FRP.

Secondly, the power plant site itself will not be used for assembling and launching the pipe segments, as would be done in Hawaii. Puerto Yabucoa, a large commercial tanker harbor, is located only a few miles from the proposed power plant site at Punta Yeguas. Assuming enough area would be available adjacent to the tanker terminal, the ground could be cleared and set up for fabrication of both the concrete and FRP pipe sections. The conceptual design and construction of the FRP cold water pipe is detailed in Section VI. The concrete pipe sections can be loaded individually onto barges in the tanker terminal and towed to the appropriate shallow water installation site as required.

Figure VII-3 shows that a 40 MWe plant in Puerto Rico would require three full years of construction time. The fact that this schedule is several months longer than for Hawaii is due primarily to the much longer runs of shallow seawater pipe required in Puerto Rico. The significant tasks of the construction procedure are detailed as follows:

Prepare construction sites

The preparation of construction sites in Puerto Rico will involve the relatively small area on the beach at Punta Yeguas for the power plant site itself, as well as a large area (40 acres or more) adjacent to the oil tanker terminal for pipe fabrication, storage, equipment staging, etc. Subtasks 1.1 through 1.4 include construction and/or improvement of access roads; clearing, grading, and limited excavation of pipe fabrication areas; installation of electric power lines, water, sewage, area lighting, and telephone service; and installation of security fences and temporary office buildings. This portion of the site preparation will require about 10 months.

Subtasks 1.5 and 1.6 are key pacing items which involve the detailed design, construction, and on-site installation of the equipment necessary for fabrication of both the concrete and FRP seawater pipes. Preliminary estimates from industry representatives indicate that at least twelve months will be required for completion of the FRP pipe manufacturing facility. Consequently, the fabrication of FRP pipe sections (Subtask 1.7) is scheduled to begin in the thirteenth month of construction operations. Likewise, the completion of the concrete pipe fabrication facility will require fifteen months, and therefore, fabrication of concrete pipe sections (Subtask 1.8) is scheduled to begin in the sixteenth month.

Fabrication of the FRP cold water pipe assembly can be accomplished in twelve months utilizing two spools on an assembly line (see Section VI). Fabrication of the concrete pipe sections for the shallow water portions of the seawater pipe system will also require approximately twelve months.

Install cold water pipes

The first step in preparing for the installation of the cold water pipe system is to mobilize the vessels required for the various stages

of pipe installation. In fact, because there will be two separate kinds of cold water pipe, subtask 2.1 will be accomplished in two steps. The first step is to mobilize the vessels to be used in the installation of the shallow water pipelines: barges, workboats, dredge, jack-up rig, etc. The second step in vessel mobilization will occur several months later, just prior to the completion of the FRP cold water pipe assembly. These vessels will be required for installation of the deepwater anchor blocks, visual pipeline route survey, placement of cold water pipe pull-down lines, and one or more tugboats to haul the cold water pipe assembly into location.

Once the first phase of vessel mobilization is accomplished, dredging can begin at the seaward end of the shallow water trench for the two, parallel cold water intake and discharge lines (subtask 2.4).

Installation of the concrete pipe sections will begin at the seaward end of the route, two to three months after the trenching operations have started, as shown in subtask 2.5. The first section of concrete pipe to be installed will be a specially-designed transition section which will mate with the FRP pipe to be installed later. Pipeline installation will then continue concurrently with trenching operations until a sufficient number of pipe sections have been placed such that inspection, backfilling, and burying of the pipe can start. These three operations will then continue simultaneously until both parallel cold water lines are trenched, installed, inspected, and buried.

In the meantime, fabrication of the FRP deep water pipe will be nearing completion (subtask 1.7). About two months prior to completion of the FRP pipe, the required vessels will be mobilized (subtask 2.1) and installation of the concrete anchor blocks can begin (subtask 2.2). Three to four weeks will be allowed for installation and rigging of the anchor blocks. Another four to five weeks will be required for the actual haul-out, rigging, and final installation of the 5000-foot section of FRP pipe (subtask 2.3). These subtasks are further detailed

in Section VI. Once the FRP deepwater pipe has been anchored securely and inspected by a manned submersible, the vessels used in this phase can be released for other duties.

Install warm water pipe

A warm water discharge pipe will be installed to insure that the cooler warm water from the evaporators is carried out to sea beyond the near-shore, shallow water zone. Installation of this single concrete pipeline will proceed in much the same manner as the dual cold water lines. First, a terminal block is installed at the seaward end of the pipeline route, as indicated in subtask 3.1. This can be done by utilizing some of the same vessels which were used for installation of the FRP pipe anchor blocks. Next, the trenching can be started, beginning at the offshore end and working toward the beach. Installation of pipe sections will begin after about 1000 feet of trenching has been done. About one month after the first few hundred feet of pipeline has been installed, the inspection, backfilling, and burying operations can begin. These three operations will then continue simultaneously until the discharge line is completed (subtasks 3.2, 3.3, and 3.4). This will complete the offshore pipelines, and all the remaining vessels can be released for demobilization.

Develop power plant site

Development of the plant site and construction of the power plant will be carried out in six subtasks. The first job, (subtask 4.1) is to excavate the troughs for the seawater intake and discharge plenums, requiring approximately three months. A four-month period will then be required for erecting the foundations and walls, and a separate four-month period (subtask 4.3) for installation of utilities and construction of the large gantry cranes for handling the power plant components. Assuming all the power plant components have been shipped to the site on time, a period of approximately five months will be

needed for their installation (subtask 4.4). Ammonia loop piping and plumbing (subtask 4.5) can be started shortly after the first 10 MWe power module components are installed, taking about four and one-half months for completion. Finally, the electric power sub-station and auxiliaries can be installed over a three-month period as shown in subtask 4.6.

All of these subtasks will overlap to some degree as shown in Figure VII-3 , so that the entire power plant site development phase should take no more than a full year. At this point, the plant will be ready for start-up, initial testing, and useful power generation.

10 MWe PLANT, PUERTO RICO

The construction schedule for a 10 MWe OTEC plant in Puerto Rico is virtually identical to that for a 40 MWe plant; either plant requiring three full years of construction time. The main reason for this is the fact that the seawater pipes for the 10 MWe plant are not much smaller than the pipes for the 40 MWe plant, and, consequently, the time required for manufacture and installation of the 10 MWe pipes will be almost the same as for the larger pipes. In both cases, the pipeline installation operations are the key elements in determining the total time for plant construction, and therefore, both plant sizes will require three years' time.

The only task in which there will be some savings in construction time is the development of the power plant site itself. Naturally, since only one 10 MWe power module will be installed as opposed to four, there will be significant savings in time and costs for subtasks 4.1 through 4.6. Figure VII-4 shows a net difference of approximately three months for task 4.0.

Figure VII-1 Construction Schedule, 40 MWe Plant, Hawaii

LEGEND	
Construction Schedule 10 MWe Land Based OTEC Power Plant Keahole Point, Hawaii	
	Months to completion of subtask
DESCRIPTION	
1.0 Prepare construction sites	
1.1 Construct access roads	
1.2 Clear & grade fabrication site	
1.3 Install utilities	
1.4 Erect fences & temporary bldgs.	
1.5 Design & construct fab. equip.	
1.6 Install pipe fabrication equip.	
1.7 Fabricate pipe sections	
2.0 Develop plant site, Phase I	
2.1 Excavate pipe launch ways	
2.2 Erect pipe handling equipment	
2.3 Excavate near-shore trenches	
3.0 Install cold water pipes	
3.1 Mobilize vessels	
3.2 Install deep water terminations	
3.3 Prepare pipeline route	
3.4 Install deep water pipe	
3.5 Install shallow water pipes	
3.6 Inspect & install screen	
3.7 Backfill & bury	
4.0 Install warm water pipe	
4.1 Land & cement termination	
4.2 Prepare pipeline route	
4.3 Demobilize DP drillship	
4.4 Install pipe sections	
4.5 Inspect & install screen	
4.6 Backfill & bury	
5.0 Develop plant site, Phase II	
5.1 Excavate intake troughs	
5.2 Erect foundations & walls	
5.3 Install power plant components	
5.4 Install piping	
5.5 Erect sub-station, auxiliaries	

REMARKS:

- Tasks 3.0 and 4.0 will be accomplished on a 10 hour/day 5 day/week basis to minimize the days required for the DP drillship.
- All other tasks are based on standard 40 hour work week, utilizing local labor force wherever possible.

Figure VII-2 Construction Schedule, 10 Mw Plant, Hawaii

LEGEND		Months to completion of subtask																																																							
DESCRIPTION																																																									
1	1.0 Prepare construction site																																																								
2	1.1 Construct/improve access roads																																																								
3	1.2 Clear & grade fabrication sites																																																								
4	1.3 Install utilities																																																								
5	1.4 Erect fences & temporary bldgs.																																																								
6	1.5 Design & construct fab. equip.																																																								
7	1.6 Install pipe fabrication equip.																																																								
8	1.7 Fabricate FRP pipe																																																								
9	1.8 Fabricate concrete pipe																																																								
10																																																									
11	2.0 Install cold water pipes																																																								
12	2.1 Mobilize vessels																																																								
13	2.2 Install anchor blocks																																																								
14	2.3 Install FRP deep water pipe																																																								
15	2.4 Prepare shallow water trench																																																								
16	2.5 Install shallow water pipes																																																								
17	2.6 Inspect, backfill & bury																																																								
18	2.7 Install screen																																																								
19																																																									
20	3.0 Install warm water pipe																																																								
21	3.1 Land termination block																																																								
22	3.2 Prepare shallow water trench																																																								
23	3.3 Install pipeline sections																																																								
24	3.4 Inspect, backfill & bury																																																								
25	3.5 Demobilize vessels																																																								
26																																																									
27	4.0 Develop power plant site																																																								
28	4.1 Excavate seawater troughs																																																								
29	4.2 Erect foundations and walls																																																								
30	4.3 Install cranes & utilities																																																								
31	4.4 Install power plant components																																																								
32	4.5 Install piping																																																								
33	4.6 Erect sub-station, auxiliaries																																																								
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REMARKS:

1. Sub-task 1.7 will be accomplished utilizing 24 hour/day 7 day/week

2. Sub-tasks 2.2 and 2.3 will require continuous at-sea operations until completion

3. All other sub-tasks are based on standard 40 hour work week, utilizing local labor force wherever possible.

Figure VII-3 Construction Schedule, 40 MWe Plant, Puerto Rico

LEGEND		Months to completion of subtask																																																								
DESCRIPTION																																																										
1	1.0 Prepare construction site																																																									
2	1.1 Construct/improve access roads																																																									
3	1.2 Clear & grade fabrication sites																																																									
4	1.3 Install utilities																																																									
5	1.4 Erect fences & temporary bldgs.																																																									
6	1.5 Design & construct fab. equip.																																																									
7	1.6 Install pipe fabrication equip.																																																									
8	1.7 Fabricate FRP pipe																																																									
9	1.8 Fabricate concrete pipe																																																									
10																																																										
11	2.0 Install cold water pipes																																																									
12	2.1 Mobilize vessels																																																									
13	2.2 Install anchor blocks																																																									
14	2.3 Install FRP deepwater pipe																																																									
15	2.4 Prepare shallow water trench																																																									
16	2.5 Install shallow water pipes																																																									
17	2.6 Inspect, backfill & bury																																																									
18	2.7 Install screen																																																									
19																																																										
20	3.0 Install warm water pipe																																																									
21	3.1 Land termination block																																																									
22	3.2 Prepare shallow water trench																																																									
23	3.3 Install pipeline sections																																																									
24	3.4 Inspect, backfill & bury																																																									
25	3.5 Demobilize vessels																																																									
26																																																										
27	4.0 Develop power plant site																																																									
28	4.1 Excavate seawater troughs																																																									
29	4.2 Erect foundations and walls																																																									
30	4.3 Install cranes & utilities																																																									
31	4.4 Install power plant components																																																									
32	4.5 Install piping																																																									
33	4.6 Erect sub-station, auxiliaries																																																									
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REMARKS:

1. Sub-task 1.7 will be accomplished utilizing 24 hour/day 7 day/week.

2. Sub-tasks 2.2 and 2.3 will require continuous at-sea operations until completion.

3. All other sub-tasks are based on standard 40 hour work week, utilizing local labor force wherever possible.

Figure VII-4 Construction Schedule, 10 MWe Plant, Puerto Rico

SECTION VIII COST ESTIMATES

INTRODUCTION

The cost estimates for the two OTEC plant sizes in two locations were developed using the conceptual designs outlined earlier in this report, together with the DOE-approved Work Breakdown Structure (WBS) shown in Figure I-2. Where possible, costs were estimated based directly in 1980 dollars; otherwise, 1978 estimates were increased to 1980 dollars using a 7-percent annual rate. For almost every element of the WBS, the estimating was done using a "bottom-up" technique; that is, the estimates were independent and reflect, for instance, number of men times the rate per hour times the number of hours. The schedules used to estimate the number of months various personnel are needed to accomplish a specific task, are included in Figures II-7 through II-10.

The cost of power plant components were estimated starting with the TRW power module (as outlined in the TRW June 1978 presentation) as approved by the DOE, and then adjusted by Fluor for the special characteristics of a land-based OTEC plant versus a floating platform configuration. In addition to the general areas in which Deep Oil Technology and the Fluor Corporation were most qualified to estimate costs, the following contributions are recognized:

- Evans-Hamilton, Inc. (General site data and survey costs)
- University of Hawaii (Site data-Hawaii)
- Dillingham Corporation (Site data and construction costs - Hawaii)
- General Construction Company (Site data and construction costs-Hawaii)
- Center for Energy and Environment Research (Site data-Puerto Rico)

Misener Marine Construction (Site data and construction costs-Puerto Rico)

Ameron (Concrete pipe costs)

Fiberglass Structural Engineering (FRP pipe costs).

It should be emphasized that the OTEC plant conceptual designs, and therefore the resulting design and construction costs, are quite site specific. However, this impact is most significant in the area of construction and deployment costs (WBS element 3.0). For this reason, costs for General Management (WBS 1.0), Design (WBS 2.0), and System Operation and Support (WBS 4.0) are presented first for both Hawaii and Puerto Rico, with minor differences noted. Then the Acquisition/Construction and Deployment (WBS 3.0) costs are detailed for each site in separate sections.

GENERAL MANAGEMENT

Several assumptions are made regarding the overall design, construction and operation schedules, as these have an impact on the costs of general management. First, it has been assumed that the conceptual design phase has been completed, and that preliminary design begins when the DOE selects the OTEC plant size and location. As shown in the previous section, the schedule calls for eight months of preliminary design, followed by five months for review, request for proposals, and selection of the contract design contractor. Contract design of six months is followed by a one-month review period prior to initiating detail design and construction. This results in a 20-month design phase, during which a general management team is proposed as follows:

The three upper level managers would likely come from government, while the support managers would be provided by an integration contractor. In addition, a representative from the local utility company would join the management team for the contract design phase. Design phase management is estimated:

$$\begin{array}{rcl}
 6 \text{ men} \times \$40/\text{hr.} \times 173 \text{ hr./mo.} \times 20 \text{ mo.} & = & \$830,400 \\
 1 \text{ man} \times \$40/\text{hr.} \times 173 \text{ hr./mo.} \times 6 \text{ mo.} & = & \underline{41,500} \\
 & & \$871,900 \quad 0.9\text{M} \quad \underline{\text{WBS 1.1}}
 \end{array}$$

The same management staff (including the utilities representative) may be assumed for the acquisition/construction and deployment phase, with each supporting contractor providing its own internal management; the schedule length difference between plant sizes and sites are shown in the previous section. Acquisition/construction and deployment phase management is estimated:

$$\begin{array}{rcl}
 \text{Hawaii: } (10 \text{ MWe}) \text{ 7 men} \times \$40/\text{hr.} \times 173 \text{ hr./mo} \times 32 \text{ mo} & = & \\
 & & \$1,550,100 \quad 1.6 \text{ M} \quad \underline{\text{WBS 1.2}} \\
 (40 \text{ MWe}) \text{ 7 men} \times \$40/\text{hr.} \times 173 \text{ hr./mo.} \times 36 \text{ mo} & = & \\
 & & \$1,743,800 \quad 1.8\text{M} \quad \underline{\text{WBS 1.2}} \\
 \text{Puerto Rico: } (10 \text{ MWe}) \text{ 7 men} \times \$40/\text{hr.} \times 173 \text{ hr./mo} \times 38 \text{ mo} & = & \\
 & & \$1,840,700 \quad 1.9\text{M} \quad \underline{\text{WBS 1.2}} \\
 (40 \text{ MWe}) \text{ 7 men} \times \$40/\text{hr.} \times 173 \text{ hr./mo} \times 38 \text{ mo} & = & \\
 & & \$1,840,700 \quad 1.9\text{M} \quad \underline{\text{WBS 1.2}}
 \end{array}$$

During the first two years of operation, it is expected that a heavy emphasis will be placed on testing and data gathering. Therefore, management will continue to acquire a full-time staff with cooperation from government, integration contractor, and utility; a team is proposed as follows:

- Project Manager (Government)
- 2 Technical Support Managers (Integration contractor)
- Liaison Representative (Utility) .

During the subsequent eight years of operation, the primary purpose of the OTEC plant will be to demonstrate delivery of power to the local grid and to observe long-term environmental effects. Limited government management is anticipated, with a single resident technical support manager:

Project Manager - 1/2 time (Government)

Onsite Technical Support Manager (Integration contractor).

System operations and support phase management is estimated:

4 men x \$40/hr. x 173 hr./mo. x 24 mo. = \$664,300

1.5 men x \$40/hr. x 173 hr./mo. x 96 mo. = \$996,500

\$1,660,800 1.7M WBS 1.3

DESIGN

The design of the land-based OTEC plant is carried out in several distinct stages: conceptual design, preliminary design, contract design, and engineering and detail design. The latter stage is actually carried out during construction of the plant, so will be costed in that section of the work breakdown structure (WBS 3.11). As previously mentioned, the conceptual design is assumed complete.

Preliminary design is estimated to require a 12-man design team for the scheduled eight months. In addition, Evans-Hamilton has estimated that a detailed site survey would cost approximately \$1,700,000; this has been allocated to preliminary and contract design, \$1,000,000 and \$700,000 respectively. Preliminary design is estimated:

12 men x \$30/hr x 173 hr/mo x 8 mo = \$ 498,200

Site Survey (partial)

= 1,000,000

\$1,498,200

1.5M WBS 2.2

Little or no difference is expected between 10 and 40 MWe plant size for contract design (i.e. specification writing). Using the applicable items of the fourth level of the work breakdown structure

as a guide, the contract design is estimated:

2.3.1 Design Management: 3 men x \$40/hr x 173 hr/mo x 6 mo = \$124,600
2.3.2 Systems Engineering: 4 men x \$30/hr x 173 hr/mo x 6 mo = 124,600
2.3.4 Land-based Containment
System Design: 12 men x \$30/hr x 173 hr/mo x 6 mo = 373,700
2.3.5 Seawater Pipe
System Design: Hawaii
5 men x \$30/hr x 173 hr/mo x 6 mo = \$155,700
Puerto Rico
10 men x \$30/hr x 173 hr/mo x 6 mo = \$311,400
2.3.6 Power System
Design: 12 men x \$30/hr x 173 hr/mo x 6 mo = \$373,700
2.3.7 Energy Transfer
System Design: 2 men x \$30/hr x 173 hr/mo x 6 mo = \$ 62,300
Site Survey
(Partial): = 700,000

Totaling these costs for the two sites results in the estimates:

Hawaii:	\$1,914,600	2.0M	<u>WBS 2.3</u>
Puerto Rico:	\$2,070,300	2.1M	<u>WBS 2.3</u>

SYSTEM OPERATION AND SUPPORT

Of the WBS elements covering operation and support of the OTEC plant over a 10-year period, only onshore operational support is cost estimated. There are no costs associated with offshore operational support, costs for OTEC system tests have been included in general management and onshore operational support, and system refit and modification costs have not been estimated at this time. The cost of system disposal should be more than covered by the scrap value of the plant components.

Estimating for onshore operational support is as follows:

4.2.1 Plant Personnel:

5 janitors x \$5/hr x 173 hr/mo x 120 mo = \$519,000
1 plant engineer x \$30/hr x 173 hr/mo x 120 mo = \$622,800

2 security x \$8/hr x 173 hr/mo x 120 mo x 3 shifts	= \$996,500
1 guide x \$8/hr x 173 hr/mo x 120 mo	= <u>166,100</u>
	\$2,304,400

OTEC Personnel (10 MWe)

1 project/test manager x \$40/hr x 173 hr/mo x 120 mo	= 830,400
1 oceanographer x \$30/hr x 173 hr/mo x 24 mo	= 124,600
2 mechanical engineers x \$30/hr x 173 hr/mo x 24 mo	= 249,100
1 mechanical engineer x \$30/hr x 173 hr/mo x 96 mo	= 498,200
1 chemical engineer x \$30/hr x 173 hr/mo x 24 mo	= 124,600
1 control system engineer x \$30/hr x 173 hr/mo x 120 mo	= 622,800
1 biologist/chemist x \$30/hr x 173 hr/mo x 24 mo	= 124,600
2 computer analysts x \$30/hr x 173 hr/mo x 24 mo	= 249,100
5 technicians x 2 shifts x \$20/hr x 173 hr/mo x 24 mo	= 830,400
2 technicians x 2 shifts x \$20/hr x 173 hr/mo x 96 mo	= <u>1,328,600</u>
	\$4,982,400

OTEC Personnel (40 MWe), add:

1 control systems engineer x \$30/hr x 173 hr/mo x 120 mo	= 622,800
1 computer analyst x \$30/hr x 173 hr/mo x 24 mo	= 124,600
3 technicians x 2 shifts x \$20/hr x 173 hr/mo x 24 mo	= 498,200
1 technician x 2 shifts x \$20/hr x 173 hr/mo x 96 mo	= <u>664,300</u>
	\$6,892,300

Total Onshore Personnel:

(10 MWe) 2,304,400 + 4,982,400	= 7,286,800
(40 MWe) 2,304,400 + 6,892,300	= 9,196,700

4.2.2 Transportation: air travel round trip to/from Washington, D. C.

Hawaii: 3 men x 4 trips/yr x \$700/trip x 2 yrs	= \$16,800
2 men x 2 trips/yr x \$700/trip x 8 yrs	= <u>\$22,400</u>
	\$39,200

Puerto Rico: 3 men x 4 trips/yr x \$350/trip x 2 yrs	= \$ 8,400
2 men x 2 trips/yr x \$350/trip x 8 yrs	= <u>11,200</u>
	\$19,600

4.2.3 Maintenance and Repair (ROM estimate):

(10 MWe) \$250,000/yr x 10 yrs = \$ 2,500,000

(40 MWe) \$500,000/yr x 10 yrs = \$ 5,000,000

4.2.4 Consumables (fuel oil, lube oil, misc; ROM estimate):

(10 MWe) \$50,000/yr x 10 yrs = \$ 500,000

(40 MWe) \$100,000/yr x 10 yrs = \$1,000,000

4.2.5 Support Equipment: assumed included in capital costs.

4.2.6 Training: assumed to be approximately 5 percent of personnel costs:

(10 MWe) 0.05 x \$7,286,800 = \$364,300

(40 MWe) 0.05 x \$9,196,700 = \$459,800

In summary, then, for Operational Support - Onshore:

Hawaii: (10 MWe) 7,286,800 + 39,200 + 2,500,000 + 500,000 +
364,300 = \$10,690,300 10.7M WBS 4.2

(40 MWe) 9,196,700 + 39,200 + 5,000,000 + 1,000,000 +
459,800 = \$15,695,700
15.7M WBS 4.2

Puerto Rico: (10 MWe) 7,286,800 + 19,600 + 2,500,000 + 500,000 +
364,300 = \$10,670,700 10.7M WBS 4.2

(40 MWe) 9,196,700 + 19,600 + 5,000,000 + 1,000,000 +
459,800 = \$15,676,100
15.7M WBS 4.2

ACQUISITION/CONSTRUCTION AND DEPLOYMENT

This element of the WBS represents the major cost item in the development, construction and operation of the land-based OTEC plant system. As such, most of the effort during this study was concentrated on estimating the costs during this phase. Emphasis was placed on obtaining comprehensive and specific site data, through use of published charts and reports, as well as a visit to each site. Contractors familiar with construction in each area were contacted and their comments and suggestions solicited.

Once a design concept had been developed for each site, major potential pipe manufacturers were asked to contribute design and cost information, and the resources of Fluor Corporation were utilized to assist in the cost estimating of on-shore construction. As mentioned previously, the power module component costs were taken from the June 1978 TRW presentation and subsequently adjusted by Fluor to reflect cost increases to 1980 and differences between land-and platform-based OTEC plants.

In this phase of the cost estimate, the two work breakdown structure elements not applicable to the land-based OTEC system are the Platform System (WBS 3.1) and the Energy Utilization System (WBS 3.7). The other elements are outlined below, with a complete description given for the plant located in Hawaii, and additions and deletions representing conceptual differences given in a separate section for the plant located in Puerto Rico.

Hawaii

The land-based containment system has been estimated based primarily on published site data and visit information, then calculated by Fluor and modified somewhat by Deep Oil. The first three fourth-level WBS elements, Structure, Facility Support Systems, and Outfit and Furnishings, are grouped together for convenience. Working directly from the Fluor estimate:

Site Development. Blasting and excavating in lava rock costs approximately \$70/yd.³, based upon recent experience with a small-boat harbor in the Keahole Point area. The only major excavation is for the two seawater troughs. No breakwater is necessary and shoring and dewatering is not possible. Due to the integrity of the lava rock, no backfill of imported material is expected, and disposal of spoils will be negligible. The following items are included in site development costs:

Clear and Grub: (10 MWe) \$30,000
 (40 MWe) \$30,000

Blast and Excavate: (10 MWe) 2 troughs x 94' x 86' x 68' ÷ 27 ft³/yd
 = 40,700 yd³

40,700 yd³ x \$70/yd³ = \$2,850,000

(40 MWe) 2 troughs x 216' x 86' x 68' ÷ 27 ft³/yd³
 = 93,600 yd³

93,600 yd³ x \$70/yd³ = \$6,550,000

Excavation and Backfill: (10 MWe) \$100,000
 (40 MWe) \$300,000

Restore Shoreline: (10 MWe) \$400,000
 (40 MWe) \$400,000

Miscellaneous Improvements: (10 MWe) \$450,000
 (40 MWe) \$500,000

Totals: (10 MWe) \$3,830,000
 (40 MWe) \$7,780,000

Concrete. The necessary reinforced structural concrete as estimated by Fluor may be reduced by about 25 percent due to the integrity of the lava rock and the reduction in the amount of excavation:

(10 MWe) \$2,885,000 x 0.75 = \$2,163,800

(40 MWe) \$4,150,000 x 0.75 = \$3,112,500

Buildings. No change is required in the estimate by Fluor:

(10 MWe) \$300,000

(40 MWe) \$300,000

Steel. No change is required in the estimate by Fluor:

(10 MWe) \$800,000

(40 MWe) \$1,000,000

In summation, for the first three elements in WBS 3.2, the total cost is estimated:

$$(10 \text{ MW}_e) \$3,830,000 + \$2,163,800 + \$300,000 + \$800,000 = \$7,093,800$$

$$\$7,093,800 \times (1.07)^2 = \$8,121,700$$

$$(40 \text{ MW}_e) \$7,780,000 + \$3,112,500 + \$300,000 + \$1,000,000 = \$12,192,500$$

$$\$12,192,500 \times (1.07)^2 = \$13,959,200$$

3.2.4 Seawater Systems. As the seawater intake and discharge pipes are costed elsewhere in this estimate, as are the excavation and structure of the seawater troughs, the seawater pumps are the only items included here (WBS 3.2.4). These are taken from the TRW estimate, adjusted by Fluor:

$$(10 \text{ MW}_e) \text{ 2 pumps; } \$870,000 \times (1.07)^2 = \$996,100$$

$$(40 \text{ MW}_e) \text{ 8 pumps; } \$3,480,000 \times (1.07)^2 = \$3,984,300.$$

Biofouling and Corrosion Control has not been costed at this time.

In summary, then, for Land-based Containment System:

$$(10 \text{ MW}_e) \$8,121,700 + \$996,100 = \$9,117,800 \quad 9.2\text{M} \quad \underline{\text{WBS 3.2}}$$

$$(40 \text{ MW}_e) \$13,959,200 + \$3,984,300 = \$17,943,500 \quad 18.0\text{M} \quad \underline{\text{WBS 3.2}}$$

The Cold Water Pipe System costs are estimated using materials and fabrication figures supplied by Ameron, and a tentative pipeline route shown earlier in this report. This route results in an estimated 8300 feet of concrete pipe for the intake and 2400 feet for the discharge. Separate cost estimates are provided for design, construction and mobilization of the pipe fabrication and handling equipment; these are amortized over the total estimated pipe length of 12,000 feet. Cost figures from Ameron are also adjusted for the anticipated 7 percent inflation rate from 1978 to 1980. The cold water pipe costs are estimated:

$$\begin{aligned} (10 \text{ MW}_e) \quad & \$8,000,000 \div 12,000 \text{ ft.} = \$667/\text{ft.} \text{ (mobilization)} \\ & (8300 \text{ ft} + 2500 \text{ ft}) \times (\$1000/\text{ft.} + \$667/\text{ft.}) \times (1.07)^2 = \\ & \quad \$20,612,300 \end{aligned}$$

$$\begin{aligned}
 (40 \text{ MW}_e) \quad & \$10,000,000 \div 12,000 \text{ ft.} = \$833/\text{ft.} \text{ (mobilization)} \\
 & (8300 \text{ ft.} + 2500 \text{ ft.}) \times (\$1750/\text{ft} + \$833/\text{ft.}) \times (1.07)^2 \\
 & = \$31,938,600
 \end{aligned}$$

Requirements for intake and discharge screens are estimated to be minimal, so the figures above are believed adequate to cover their costs. As the concrete pipe is virtually inert in seawater, no significant costs are expected for biofouling or corrosion control. The pipe anchoring system costs, significant primarily for the cold water intake pipe, are included in WBS 3.9.3, Seawater Pipe Deployment. In summary, then, the Cold Water Pipe System is estimated:

(10 MW _e)	\$20,612,300	20.7M	<u>WBS 3.3</u>
(40 MW _e)	\$31,938,600	32.0M	<u>WBS 3.3</u>

The Warm Water Pipe system costs have been estimated in a similar manner. As the warm water intake is designed as an open channel, carved from the lava rock, only the 1200-foot warm water discharge pipe need be estimated:

$$\begin{aligned}
 (10 \text{ MW}_e) \quad & (1200 \text{ ft}) \times (\$1000/\text{ft} + \$667/\text{ft}) \times (1.07)^2 = \$2,290,300 \\
 & \quad \quad \quad 2.3\text{M} \quad \quad \quad \text{WBS 3.4} \\
 (40 \text{ MW}_e) \quad & (1200 \text{ ft}) \times (\$1750/\text{ft} + \$833/\text{ft}) \times (1.07)^2 = \$3,548,700 \\
 & \quad \quad \quad 3.6\text{M} \quad \quad \quad \text{WBS 3.4}
 \end{aligned}$$

As previously indicated, the power system costs are based on data from TRW, modified and adjusted by Fluor, then increased for inflation by 7 percent per year. Estimates are as follows:

$$\begin{aligned}
 3.5.1 \quad \text{Evaporator System} \quad & (10 \text{ MW}_e) \quad \$5,040,000 \times (1.07)^2 = \$5,770,300 \\
 & (40 \text{ MW}_e) \quad \$18,000,000 \times (1.07)^2 = \$20,608,200 \\
 3.5.2 \quad \text{Condenser System} \quad & (10 \text{ MW}_e) \quad \$4,360,000 \times (1.07)^2 = \$4,991,800 \\
 & (40 \text{ MW}_e) \quad \$15,490,000 \times (1.07)^2 = \$17,734,500
 \end{aligned}$$

- 3.5.3 Ammonia System (10 MW_e) $\$180,000 \times (1.07)^2 = \$206,100$
 (40 MW_e) $\$720,000 \times (1.07)^2 = \$824,300$
- 3.5.4 Purge System (10 MW_e) $\$100,000 \times (1.07)^2 = \$114,500$
 (40 MW_e) $\$400,000 \times (1.07)^2 = \$458,000$
- 3.5.5 Generator System (10 MW_e) $\$1,450,000 \times (1.07)^2 = \$1,660,100$
 (40 MW_e) $\$5,800,000 \times (1.07)^2 = \$6,640,400$
- 3.5.6 Auxiliary Systems (10 MW_e) $\$380,000 \times (1.07)^2 = \$435,100$
 (40 MW_e) $\$1,520,000 \times (1.07)^2 = \$1,740,200$
- 3.5.7 Instrumentation, Control System (10 MW_e) $\$130,000 \times (1.07)^2 =$
 $\$148,800$
 (40 MW_e) $\$530,000 \times (1.07)^2 = \$606,800$
- 3.5.8 Biofouling, Corrosion Control (10 MW_e) $\$200,000 \times (1.07)^2 =$
 $\$229,000$
 (40 MW_e) $\$800,000 \times (1.07)^2 = \$915,900$

In summary, then, the Power System is estimated:

$$\begin{aligned} (10 \text{ MW}_e) & \$5,770,300 + \$4,991,800 + \$206,100 + \$114,500 + \$1,660,100 \\ & + \$435,100 + \$148,800 + \$229,000 = \$13,555,700 \\ 13.6\text{M}^* & \quad \quad \quad \underline{\text{WBS 3.5}} \end{aligned}$$

$$\begin{aligned} (40 \text{ MW}_e) & \$20,608,200 + \$17,734,500 + \$824,300 + \$458,000 + \$6,640,400 \\ & + \$1,740,200 + \$606,800 + \$915,900 = \$49,528,300 \\ 49.6\text{M}^* & \quad \quad \quad \underline{\text{WBS 3.5}} \end{aligned}$$

*Note that these cost estimates (WBS 3.5) were revised upward to be 22.0 M and 88.0 M respectively at the recent direction of the Department of Energy.

The energy transfer system for the land-based OTEC plant includes only power conditioning and control, as well as an allowance for fittings and connections. The other fourth level elements of the work breakdown structure are not applicable to the land-based plant. Again, the costs included here are based on preliminary study of the power system by Fluor.

- 3.6.1 and 3.6.2 Power Control and Bus, Power Conditioning
 (10 MW_e) $\$290,000 \times (1.07)^2 = \$332,000$
 (40 MW_e) $\$1,140,000 \times (1.07)^2 = \$1,305,200$

3.6.5 Fittings, Connections, Support (ROM estimate)

$$(10 \text{ MW}_e) \quad \$100,000 \times (1.07)^2 = \$114,500$$

$$(40 \text{ MW}_e) \quad \$100,000 \times (1.07)^2 = \$114,500$$

In summary, then, the Energy Transfer System is estimated:

$$(10 \text{ MW}_e) \quad \$332,000 + \$114,500 = \$446,500 \quad 0.5\text{M} \quad \text{WBS 3.6}$$

$$(40 \text{ MW}_e) \quad \$1,305,200 + \$114,500 = \$1,419,700 \quad 1.5\text{M} \quad \text{WBS 3.6}$$

Acceptance testing of the land-based OTEC plant is assumed to take place during the last two months of the Acquisition/Construction and Deployment phase; these costs are allocated in work breakdown structure element 3.8.6. Quite obviously, there is no need for dockside tests, builders trials or platform acceptance tests. However, a significant (and difficult to estimate) cost may be expected for special tests required for "proof of concept"; that is, small-scale laboratory flow testing to confirm effects of pipe size on plant residual power requirements, and large-scale laboratory and ocean testing of the pipe installation methods. This latter testing is particularly necessary for deep-water installation of the cold water intake pipe in both Hawaii and Puerto Rico.

3.8.1 Test Planning (ROM estimate)

$$(10 \text{ MW}_e) \quad \$300,000$$

$$(40 \text{ MW}_e) \quad \$300,000$$

3.8.2 Special Test Facilities (ROM Estimate) (10 MW_e) \$2,000,000

$$(40 \text{ MW}_e) \quad \$3,000,000$$

3.8.6 OTEC System Acceptance Tests

$$(10 \text{ MW}_e) \quad 6 \text{ men} \times \$30/\text{hr} \times 173 \text{ hr/mo} \times 2 \text{ mo} = \$62,300$$

$$(40 \text{ MW}_e) \quad 9 \text{ men} \times \$30/\text{hr} \times 173 \text{ hr/mo} \times 2 \text{ mo} = \$93,400$$

$$(10 \text{ MW}_e) \$300,000 + \$2,000,000 + \$62,300 = \$2,362,300 \quad 2.4\text{M} \quad \text{WBS 3.8}$$

$$(40 \text{ MW}_e) \$300,000 + \$3,000,000 + \$93,400 = \$3,393,400 \quad 3.4\text{M} \quad \text{WBS 3.8}$$

The largest cost element at the third level of the work breakdown structure is in the installation and deployment of the power module components and the seawater pipe system. There are, of course, no costs associated with deployment of a platform. The installation of components of the power system into the prepared site foundations has been estimated by Fluor and is adjusted upward for inflation. Seawater pipe installation is described earlier in this report; the method and associated costs were developed by Deep Oil. A brief summary of costs is present here. Pipe installation costs include permanent anchors and pipe terminations.

3.9.2 Power System Module Deployment

$$(10 \text{ MW}_e) \$1,350,000 \times (1.07)^2 = \$1,545,600$$

$$(40 \text{ MW}_e) \$5,120,000 \times (1.07)^2 = \$5,861,900$$

3.9.3 Seawater Pipe System Deployment

Near-shore trenching. Based on a study of plant siting along the shoreline at Keahole Point, a trench length of 620 feet is required on the cold-water side, and 460 feet on the warm-water side; each trench will hold two pipes side-by-side. As before, the cost of blasting and excavating in lava rock is estimated at \$70 per cubic yard. Half of the spoils will be used as backfill, at a cost of \$10 per cubic yard:

$$\begin{aligned} (10 \text{ MW}_e) & (620 \text{ ft} + 460 \text{ ft}) \times (64 \text{ ft}) \times (32 \text{ ft}) \div 27 \text{ ft}^3/\text{yd}^3 = \\ & 81,900 \text{ yd}^3 \\ & 81,900 \text{ yd}^3 \times \$70/\text{yd}^3 + 81,900 \text{ yd}^3 \times 0.5 \times \$10/\text{yd}^3 = \\ & \$6,142,500 \end{aligned}$$

$$\begin{aligned}
 (40 \text{ MW}_e) \quad & (620 \text{ ft} + 460 \text{ ft}) \times (80 \text{ ft}) \times (40 \text{ ft}) \div 27 \text{ ft}^3/\text{yd}^3 = \\
 & 128,000 \text{ yd}^3 \\
 & 128,000 \text{ yd}^3 \times \$70/\text{yd}^3 + 128,000 \text{ yd}^3 \times 0.5 \times \$10/\text{yd}^3 = \\
 & \$9,600,000
 \end{aligned}$$

Cold water intake pipe.

(10 MW _e)	Materials	\$5,010,000
	Services	\$5,190,000
(40 MW _e)	Materials	\$6,985,000
	Services	\$6,670,000

Cold water discharge pipe.

(10 MW _e)	Materials	\$ 177,000
	Services	\$1,730,000
(40 MW _e)	Materials	\$ 225,000
	Services:	\$1,730,000

Warm water discharge pipe.

(10 MW _e)	Materials	\$ 114,000
	Services	\$1,420,000
(40 MW _e)	Materials	\$ 138,000
	Services	\$1,420,000

Adding these terms, pipe system deployment costs are estimated:

$$\begin{aligned}
 (10 \text{ MW}_e) \quad & \$6,142,500 + \$5,010,000 + \$5,190,000 + \$177,000 \\
 & + \$1,730,000 + \$114,000 + \$1,420,000 = \$19,783,500 \\
 & \$19,783,500 \times (1.07)^2 = \$22,650,100 \\
 (40 \text{ MW}_e) \quad & \$9,600,000 + \$6,985,000 + \$6,670,000 + \$225,000 \\
 & + \$1,730,000 + \$138,000 + \$1,420,000 = \$26,768,000 \\
 & \$26,768,000 \times (1.07)^2 = \$30,646,700
 \end{aligned}$$

In summary, then, Deployment Services are estimated:

(10 MW _e)	\$1,545,600 + \$22,650,100 = \$24,195,700	24.2M	<u>WBS 3.9</u>
(40 MW _e)	\$5,861,900 + \$30,646,700 = \$36,508,600	36.6M	<u>WBS 3.9</u>

Industrial facilities for the land-based OTEC plant in Hawaii are assumed to be included in the costs of the land-based containment system (WBS 3.2). Construction facilities (storage yards, pipe fabrication yard, etc.) will be set up near the Keahole Point site, on land already dedicated to natural resource development.

Engineering and detail design will begin approximately 2 months prior to the start of construction, and continue at varying level of effort until the plant has been put into operation. The following estimate is based upon the number of personnel required in each discipline, their charge-out rate and the length of time they need to accomplish the task.

Engineering management and planning.

(10 MWe) 10 men x \$35/hr x 173 hr/mo x 32 mo = \$1,937,600

(40 MWe) 10 men x \$35/hr x 173 hr/mo x 36 mo = \$2,179,800

Systems Design (including installation).

(10 MWe) 5 men x \$27/hr x 173 hr/mo x 32 mo = \$747,400

(40 MWe) 5 men x \$27/hr x 173 hr/mo x 36 mo = \$840,800

Land-based structure design.

(10 MWe) 6 men x \$27/hr x 173 hr/mo x 28 mo = \$ 784,700

(40 MWe) 6 men x \$27/hr x 173 hr/mo x 32 mo = \$ 896,800

Seawater pipe design.

(10 MWe) 8 men x \$27/hr x 173 hr/mo x 12 mo = \$ 448,400

(40 MWe) 8 men x \$27/hr x 173 hr/mo x 12 mo = \$ 448,400

Power system component design.

(10 MWe) 10 men x \$27/hr x 173 hr/mo x 24 mo = \$1,121,000

(40 MWe) 10 men x \$27/hr x 173 hr/mo x 28 mo = \$1,307,900

Technical manual writing.

(10 MWe) 3 men x \$27/hr x 173 hr/mo x 20 mo = \$280,300

(40 MWe) 3 men x \$27/hr x 173 hr/mo x 24 mo = \$336,300

In summary, then, Engineering and Detail Design is estimated:

(10 MWe) \$1,937,600 + \$747,400 + \$784,700 + \$448,400
+ \$1,121,000 + \$280,300 = \$5,319,400   5.4M   WBS 3.11

(40 MWe) \$2,179,800 + \$840,800 + \$896,800 + \$448,400
+ \$1,307,900 + \$336,300 = \$6,010,000   6.1M   WBS 3.11

Puerto Rico

As detailed earlier in this report, the major differences between the land-based OTEC power plant in Hawaii and Puerto Rico are 1) a land site condition in Puerto Rico more easily excavated, and 2) a longer, more formidable (and less clearly defined) bottom profile in Puerto Rico. This latter condition necessitates the use of a buoyant FRP cold water intake pipe for the deep-water zone. In this section, differences in costs between the two sites are outlined, leading to specific estimates for the Puerto Rico site near Punta Tuna. Wherever possible (or necessary), cost estimating is carried out to the fourth level of the work breakdown structure.

Site Development.

Clear and Grub: (10 MWe) \$30,000

(40 MWe) \$30,000

Excavation: (10 MWe) 40,700 yd³ x \$5/yd³ = \$203,500

(40 MWe) 93,600 yd³ x \$5/yd³ = \$468,000

Backfill-Imported Material: (10 MWe) 0.5 x 40,700 yd³ x \$5/yd³ =
\$101,800

(40 MWe) 0.5 x 93,600 yd³ x \$5/yd³ =
\$234,000

Dispose of Excess: (10 MWe) 40,700 yd³ x \$2/yd³ = \$81,400

(40 MWe) 93,600 yd³ x \$2/yd³ = \$187,200

Excavation and Backfill - All Foundations (ROM estimate):

(10 MWe) \$100,000

(40 MWe) \$300,000

Shoreline Dewatering, etc. (ROM estimate):

(10 MWe) \$500,000

(40 MWe) \$500,000

Restore Shoreline:

(10 MWe) \$400,000

(40 MWe) \$400,000

Miscellaneous Improvements:

(10 MWe) \$450,000

(40 MWe) \$500,000

Totals: (10 MWe) 1,866,700

(40 MWe) 2,619,200

Concrete. The necessary reinforced structural concrete as estimated by Fluor may be reduced by about 10 percent due to the reduction in the amount of excavation.

(10 MWe) $\$2,885,000 \times 0.90 = \$2,596,500$

(40 MWe) $\$4,150,000 \times 0.90 = \$3,735,000$

Buildings. (10 MWe) \$300,000

(40 MWe) \$300,000

Steel. (10 MWe) \$800,000

(40 MWe) \$1,000,000

For the first three elements of WBS 3.2, the total cost is estimated:

(10 MWe) $\$1,866,700 + \$2,596,500 + \$300,000 + \$800,000 =$
 $\$5,583,200$

$\$5,583,200 \times (1.07)^2 = \$6,392,200$

(40 MWe) $\$2,619,200 + \$3,735,000 + \$300,000 + \$1,000,000 =$
 $\$7,654,200$

$\$7,654,200 \times (1.07)^2 = \$8,763,300$

Seawater Systems. (10 MWe) \$996,100

(40 MWe) \$3,984,300

In summary, then, for land-based Containment System:

$$\begin{array}{llll} (10 \text{ MWe}) & \$6,392,200 + \$996,100 = \$7,388,300 & 7.4\text{M} & \text{WBS 3.2} \\ (40 \text{ MWe}) & \$8,763,300 + \$3,984,300 = \$12,747,600 & 12.8\text{M} & \text{WBS 3.2} \end{array}$$

The Cold Water Pipe system costs are estimated using the figures supplied by Ameron for concrete pipe and Fiberglass Structural Engineering for FRP pipe. As shown earlier in this report, the pipe route in Puerto Rico is significantly longer than in Hawaii, with consequently somewhat larger pipe diameter as well. As before, concrete pipe mobilization costs are amortized over the total (cold and warm water) pipe system length, and the cost estimates are adjusted for inflation. The cold water pipe costs are estimated:

$$\begin{array}{l} \text{Concrete: } (10 \text{ MWe}) \ \$8,000,000 \div 15,600 \text{ ft} = \$513/\text{ft} \text{ (mobilization)} \\ \quad (5200 \text{ ft} + 5200 \text{ ft}) \times (\$1275/\text{ft} + \$513/\text{ft}) \times (1.07)^2 = \\ \quad \quad \quad \$21,289,600 \\ \quad (40 \text{ MWe}) \ \$10,000,000 \div 15,600 \text{ ft} = \$641/\text{ft} \text{ (mobilization)} \\ \quad (5200 \text{ ft} + 5200 \text{ ft}) \times (\$2175/\text{ft} + \$641/\text{ft}) \times (1.07)^2 = \\ \quad \quad \quad \$33,530,000 \\ \\ \text{FRP: } \quad (10 \text{ MWe}) \ \$13,200,000 \times (5700 \text{ ft} \div 5000 \text{ ft}) \times (1.07)^2 = \\ \quad \quad \quad \$17,228,500 \\ \quad (40 \text{ MWe}) \ \$20,020,000 \times (5700 \text{ ft} \div 5000 \text{ ft}) \times (1.07)^2 = \\ \quad \quad \quad \$26,129,800 \end{array}$$

In summary, then, the Cold Water Pipe system is estimated:

$$\begin{array}{llll} (10 \text{ MWe}) & \$21,289,600 + \$17,228,500 = \$38,518,100 & 38.6\text{M} & \text{WBS 3.3} \\ (40 \text{ MWe}) & \$33,530,000 + \$26,129,800 = \$59,659,800 & 59.7\text{M} & \text{WBS 3.3} \end{array}$$

The warm water pipe system consists only of a concrete discharge pipe, with costs estimated:

$$\begin{array}{llll} (10 \text{ MWe}) & (5200 \text{ ft}) \times (\$1275/\text{ft} + \$513/\text{ft}) \times (1.07)^2 = \\ & \$10,644,800 & 10.7\text{M} & \text{WBS 3.4} \\ (40 \text{ MWe}) & (5200 \text{ ft}) \times (\$2175/\text{ft} + \$641/\text{ft}) \times (1.07)^2 = \\ & \$16,765,000 & 16.8\text{M} & \text{WBS 3.4} \end{array}$$

No changes are expected in the Power System costs:

(10 MWe)	13.6 M	<u>WBS 3.5</u>
(40 MWe)	49.6M	<u>WBS 3.5</u>

No changes are expected in the Energy Transfer System costs:

(10 MWe)	0.5M	<u>WBS 3.6</u>
(40 MWe)	1.5 M	<u>WBS 3.6</u>

It is expected that the major difference in the costs associated with testing will be during proof of concept demonstrations of deep water pipe installation. Within the limits of this conceptual effort, it is estimated that the cost of testing installation methods will be roughly equivalent for concrete and FRP pipe. For this reason, no change is expected in the Acceptance Testing cost:

(10 MWe)	2.4M	<u>WBS 3.8</u>
(40 MWe)	3.4M	<u>WBS 3.8</u>

Installation and deployment of the seawater pipe system is described in an earlier section of this report; due to two pipe types, and the bottom profile, the scenario in Puerto Rico is significantly different than in Hawaii. However, the power system module deployment costs should not change significantly:

3.9.2	(10 MWe)	\$1,545,600
	(40 MWe)	\$5,861,900

Near-shore trenching is far more extensive in Puerto Rico than in Hawaii, due to the relatively flat shelf extending about a mile offshore at the site. To keep the near-shore pipes from being exposed to damaging wave action, they will be buried to a water depth of 100 feet, or for a length of about 4500 feet for each of the three pipes. Trenching costs are estimated at \$10 per cubic yard (based on

conversations with Misener Marine Construction); in addition, backfill should cost about \$2 per cubic yard, with 50 percent backfill. Near-shore trenching is estimated:

$$\begin{aligned} (10 \text{ MWe}) \quad & (3 \times 4500 \text{ ft}) \times (35 \text{ ft}) \times (35 \text{ ft}) \div 27 \text{ ft}^3/\text{yd}^3 = 612,500 \text{ yd}^3 \\ & (612,500 \text{ yd}^3) \times (\$10/\text{yd}^3 + 0.50 \times \$2/\text{yd}^3) = \$6,737,500 \\ (40 \text{ MWe}) \quad & (3 \times 4500 \text{ ft}) \times (43 \text{ ft}) \times (43 \text{ ft}) \div 27 \text{ ft}^3/\text{yd}^3 = 924,500 \text{ yd}^3 \\ & (924,500 \text{ yd}^3) \times (\$10/\text{yd}^3 + 0.50 \times \$2/\text{yd}^3) = \$10,169,500 \end{aligned}$$

Deployment of the pipe in the near shore zone will be done using conventional methods; deployment of the deepwater pipe is covered in an earlier section of this report. Pipe deployment costs are summarized as follows:

Concrete pipe installation.

$$\begin{aligned} (10 \text{ MWe}) \quad & \$7,220,000 \\ (40 \text{ MWe}) \quad & \$10,920,000 \end{aligned}$$

FRP pipe installation.

$$\begin{aligned} (10 \text{ MWe}) \quad & \$1,012,000 \\ (40 \text{ MWe}) \quad & \$1,032,000 \end{aligned}$$

Total pipe installation, including trenching:

$$\begin{aligned} 3.9.3 \quad (10 \text{ MWe}) \quad & \$6,737,500 + \$7,220,000 + \$1,012,000 = \$14,969,500 \\ & \$14,969,500 \times (1.07)^2 = \$17,138,600 \\ (40 \text{ MWe}) \quad & \$10,169,500 + \$10,920,000 + \$1,032,000 = \$22,121,500 \\ & \$22,121,500 \times (1.07)^2 = \$25,326,900 \end{aligned}$$

In summary, then, Deployment Services are estimated:

$$\begin{aligned} (10 \text{ MWe}) \quad & \$1,545,600 + \$17,138,600 = \$18,684,200 \quad 18.7\text{M} \quad \underline{\text{WBS 3.9}} \\ (40 \text{ MWe}) \quad & \$5,861,900 + \$25,326,900 = \$31,188,800 \quad 31.2\text{M} \quad \underline{\text{WBS 3.9}} \end{aligned}$$

Unlike Hawaii, leased industrial facilities for the Puerto Rico land-based OTEC plant will be required for construction of the seawater pipes. Based on current lease prices of about \$1500/mo/acre, and a tentative

site next to the Puerto Yabucoa Tanker terminal north of Punta Yeguas, industrial facilities are estimated for both plant sizes:

$$(\$1500/\text{mo}/\text{acre}) \times (40 \text{ acres}) \times (30 \text{ mo}) \times (1.07)^2 = \$2,060,800$$

2.1M   WBS 3.10

For engineering and detail design, carried out concurrently with construction and deployment, the team required will be as shown for the effort in Hawaii. The only differences will be a somewhat longer design period for Engineering Management and Planning, and Systems Design, and an extra 8-man design team for the FRP pipe. These additions, and the resulting total costs, are estimated:

Engineering Management and Planning:

$$\begin{aligned} (10\text{MWe}) \quad & 10 \text{ men} \times 6 \text{ mo.} \times 173 \text{ hr./mo.} \times \$35/\text{hr.} = \$363,300 \\ (40\text{MWe}) \quad & 10 \text{ men} \times 2 \text{ mo.} \times 173 \text{ hr./mo.} \times \$35/\text{hr.} = \$121,100 \end{aligned}$$

Systems Design:

$$\begin{aligned} (10\text{MWe}) \quad & 5 \text{ men} \times 6 \text{ mo.} \times 173 \text{ hr./mo.} \times \$27/\text{hr.} = \$140,100 \\ (40 \text{ MWe}) \quad & 5 \text{ men} \times 2 \text{ mo.} \times 173 \text{ hr./mo.} \times \$27/\text{hr.} = \$46,700 \end{aligned}$$

Seawater Pipe Design:

$$\begin{aligned} (10 \text{ MWe}) \quad & 8 \text{ men} \times 12 \text{ mo} \times 173 \text{ hr/mo} \times \$27/\text{mo} = \$448,400 \\ (40 \text{ MWe}) \quad & 8 \text{ men} \times 12 \text{ mo} \times 173 \text{ hr/mo} \times \$27/\text{mo} = \$448,400 \end{aligned}$$

In summary, then, Engineering and Detail Design is estimated:

$$\begin{aligned} (10 \text{ MWe}) \quad & \$5,319,400 + \$363,300 + \$140,100 + \$448,400 = \\ & \quad \quad \quad \$6,271,200 \quad \quad \quad 6.3 \text{ M} \quad \quad \quad \text{WBS 3.11} \\ (40 \text{ MWe}) \quad & \$6,010,000 + \$121,100 + \$46,700 + \$448,400 = \$6,626,200 \\ & \quad \quad \quad \quad \quad \quad 6.7\text{M} \quad \quad \quad \text{WBS 3.11} \end{aligned}$$

COST ESTIMATE SUMMARY

The costs outlined above have been summarized to the fourth level of the Work Breakdown Structure in Table VIII-1 which follows. Costs shown are in millions of dollars, factored up to the 1980 time frame. In showing cumulative costs at the third level of the WBS, figures have

been rounded off to the next highest hundred thousand dollars (\$100,000). Costs to the third level and above are summarized in Tables II-3 through II-6 in the Summary section of this report.

Table VIII-1. SUMMARY OF COSTS TO THE FOURTH LEVEL
OF THE WORK BREAKDOWN STRUCTURE

NOTE: All costs in millions of dollars
N/A = Not applicable
N/C = Not costed

	10 MWe		40 MWe	
	Hawaii	Puerto Rico	Hawaii	Puerto Rico
1.0 GENERAL MANAGEMENT	4.2	4.5	4.4	4.5
1.1 Design Phase Management	0.9	0.9	0.9	0.9
1.1.1 Planning, Budgeting and Control				
1.1.2 Data Management				
1.1.3 Configuration Management				
1.1.4 Contract Management				
1.1.5 Financial Management				
1.1.6 Environmental, Legal, Licenses, Regulatory				
1.1.7 Procurement Planning, Implementation				
1.1.8 I.L.S. Planning				

	10 MWe		40 MWe	
	Hawaii	Puerto Rico	Hawaii	Puerto Rico
1.2 Acquisition/Construction and Deployment Phase Management	1.6	1.9	1.8	1.9
1.2.1 Planning, Budgeting and Control				
1.2.2 Data Management				
1.2.3 Configuration Management				
1.2.4 Contract Management				
1.2.5 Financial Management				
1.2.6 Environmental, Legal, Licenses, Regulatory				
1.2.7 Procurement Planning, Implementation				
1.2.8 I.L.S. Planning, Implementation				

	10 MWe		40 MWe	
	Hawaii	Puerto Rico	Hawaii	Puerto Rico
1.3 System Operations and Support Phase Management	1.7	1.7	1.7	1.7
1.3.1 Planning, Budgeting and Control				
1.3.2 Data Management				
1.3.3 Configuration Management				
1.3.4 Contract Management				
1.3.5 Financial Management				
1.3.6 Environmental, Legal, Licenses, Regulatory				
1.3.7 Procurement Planning, Implementation				
1.3.8 I.L.S. Planning, Implementation				
1.3.9 Insurance				

	10 MWe		40 MWe	
	Hawaii	Puerto Rico	Hawaii	Puerto Rico
2.0 DESIGN	3.5	3.6	3.5	3.6
2.1 Conceptual Design	*	*	*	*
2.1.1 Design Management				
2.1.2 Feasibility Studies				
2.1.3 Conceptual Design				
2.1.4 Special Studies				
2.2 Preliminary Design	1.5	1.5	1.5	1.5
2.2.1 Design Management				
2.2.2 Systems Engineering				
2.2.3 Platform System Design				
2.2.4 Land-Based Containment System Design				
2.2.5 Seawater Pipe System Design				
2.2.6 Power System Design				
2.2.7 Energy Transfer System Design				
2.2.8 Energy Utilization System Design				

*Assumed to be completed

	10 MWe		40 MWe	
	Hawaii	Puerto Rico	Hawaii	Puerto Rico
2.3 Contract Design	2.0	2.1	2.0	2.1
2.3.1 Design Management	0.12	0.12	0.12	0.12
2.3.2 Systems Engineering	0.12	0.12	0.12	0.12
2.3.3 Platform System Design	N/A	N/A	N/A	N/A
2.3.4 Land-Based Containment System Design	0.37	0.37	0.37	0.37
2.3.5 Seawater Pipe System Design	0.16	0.31	0.16	0.31
2.3.6 Power System Design	0.37	0.37	0.37	0.37
2.3.7 Energy Transfer System Design	0.06	0.06	0.06	0.06
2.3.8 Energy Utilization System Design	N/A	N/A	N/A	N/A
Site Survey	0.70	0.70	0.70	0.70

	10 MWe		40 MWe	
	Hawaii	Puerto Rico	Hawaii	Puerto Rico
3.0 ACQUISITION/CONSTRUCTION AND DEPLOYMENT	78.3	100.3	150.8	183.8
3.1 Platform System	N/A	N/A	N/A	N/A
3.1.1 Hull and Structure				
3.1.2 Position Control System				
3.1.3 Platform Support System				
3.1.4 Outfit and Furnishings				
3.1.5 Assembly Support Services				
3.1.6 Seawater Systems				
3.1.7 Biofouling, Corrosion Control				
3.2 Land-Based Containment System	9.2	7.4	18.0	12.8
3.2.1 Structure	8.12	6.39	13.96	8.76
3.2.2 Facility Support Systems				
3.2.3 Outfit and Furnishings				
3.2.4 Seawater Systems	1.00	1.00	3.98	3.98
3.2.5 Biofouling, Corrosion Control	N/C	N/C	N/C	N/C

	10 MW _e		40 MW _e	
	Hawaii	Puerto Rico	Hawaii	Puerto Rico
3.3 Cold Water Pipe System	20.7	38.6	32.0	59.7
3.3.1 Pipe System }	20.61	38.52	31.94	59.66
3.3.2 Screen				
3.3.3 CWP/Hull Transition	N/A	N/A	N/A	N/A
3.3.4 Biofouling, Corrosion Control	N/A	N/A	N/A	N/A
3.3.5 CWP Mooring, Floatation	N/A	N/A	N/A	N/A
3.3.6 CWP Embedment, Anchoring Systems	*	*	*	*
3.4 Warm Water Pipe System	2.3	10.7	3.6	16.8
3.4.1 Pipe System }	2.29	10.64	3.55	16.77
3.4.2 Screen				
3.4.3 WWP/Hull Transition	N/A	N/A	N/A	N/A
3.4.4 Biofouling, Corrosion Control	N/A	N/A	N/A	N/A
3.4.5 WWP Mooring, Flotation	N/A	N/A	N/A	N/A
3.4.6 WWP Embedment, Anchoring System	*	*	*	*

* Included with pipe deployment costs, WBS 3.9.3

	10 MW _e		40 MW _e	
	Hawaii	Puerto Rico	Hawaii	Puerto Rico
3.5 Power System	13.6	13.6	49.6	49.6
3.5.1 Evaporator System	5.77	5.77	20.61	20.61
3.5.2 Condenser System	4.99	4.99	17.73	17.73
3.5.3 Ammonia System	0.21	0.21	0.82	0.82
3.5.4 Purge System	0.11	0.11	0.46	0.46
3.5.5 Generation System	1.66	1.66	6.64	6.64
3.5.6 Auxiliary Systems	0.44	0.44	1.74	1.74
3.5.7 Instrumentation, Control System	0.15	0.15	0.61	0.61
3.5.8 Biofouling, Corrosion Control	0.23	0.23	0.92	0.92
3.6 Energy Transfer System	0.5	0.5	1.5	1.5
3.6.1 Power Control and Bus	0.33	0.33	1.31	1.31
3.6.2 Power Conditioning				
3.6.3 Riser Cable	N/A	N/A	N/A	N/A
3.6.4 Bottom Cable	N/A	N/A	N/A	N/A
3.6.5 Fittings, Connections, Support	0.11	0.11	0.11	0.11
3.6.6 Biofouling, Corrosion Control	N/A	N/A	N/A	N/A

	10 MWe		40 MWe	
	Hawaii	Puerto Rico	Hawaii	Puerto Rico
3.7 Energy Utilization System	N/A	N/A	N/A	N/A
3.7.1 Material Handling System				
3.7.2 Production System				
3.7.3 Product Transfer System				
3.7.4 Auxiliary Systems and Support				
3.8 Acceptance Testing	2.4	2.4	3.4	3.4
3.8.1 Test Planning	0.30	0.30	0.30	0.30
3.8.2 Special Test Facilities	2.00	2.00	3.00	3.00
3.8.3 Dockside Tests	N/A	N/A	N/A	N/A
3.8.4 Builders Trials	N/A	N/A	N/A	N/A
3.8.5 Platform Acceptance Tests	N/A	N/A	N/A	N/A
3.8.6 OTEC System Acceptance Tests	0.06	0.06	0.09	0.09
3.9 Deployment Services	24.2	18.7	36.6	31.2
3.9.1 Platform Deployment	N/A	N/A	N/A	N/A
3.9.2 Power System Module Deployment	1.55	1.55	5.86	5.86
3.9.3 Seawater Pipe Deployment	22.65	17.14	30.65	25.33

	10 MWe		40 MWe	
	Hawaii	Puerto Rico	Hawaii	Puerto Rico
3.10 Industrial Facilities	*	2.1	*	2.1
3.10.1 Construction Facilities				
3.10.2 Logistic Support Facilities				
3.10.3 Special Tools, Jigs, Fixtures				
3.11 Engineering And Detail Design	5.4	6.3	6.1	6.7
3.11.1 Engineering Planning and Control				
3.11.2 Construction Drawings				
3.11.3 Specifications				
3.11.4 Engineering Calculations				
3.11.5 Quality Assurance				
3.11.6 Design Integration And Control				
3.11.7 Technical Manuals and Other Data				
3.11.8 Drawing Validation				
3.11.9 Special Engineering Items				

* Included with land-based containment system WBS 3.2

	10 MW _e		40 MW _e	
	Hawaii	Puerto Rico	Hawaii	Puerto Rico
4.0 SYSTEM OPERATION AND SUPPORT	10.7	10.7	15.7	15.7
4.1 Operational Support - Offshore	N/A	N/A	N/A	N/A
4.1.1 Personnel				
4.1.2 Transportation				
4.1.3 Maintenance, Repair				
4.1.4 Consumables				
4.1.5 Support Equipment				
4.1.6 Training				
4.2 Operational Support - OnShore	10.7	10.7	15.7	15.7
4.2.1 Personnel	7.29	7.29	9.20	9.20
4.2.2 Transportation	0.04	0.02	0.04	0.02
4.2.3 Maintenance, Repair	2.50	2.50	5.00	5.00
4.2.4 Consumables	0.50	0.50	1.00	1.00
4.2.5 Support Equipment	*	*	*	*
4.2.6 Training	0.36	0.36	0.46	0.46

* Included with land-based containment system, WBS 3.2

10 MWe

40 MWe

Hawaii Puerto Rico Hawaii Puerto

4.3 OTEC System Tests

* * * *

4.3.1 Personnel

4.3.2 Transportation

4.3.3 Test Planning

4.3.4 Instruction, Data Acquisition

4.3.5 Testing

4.3.6 Evaluation

- * Included with Operations and Support Phase Management
and Operational Support - Onshore, WBS 1.3 and 3.2

	10 MWe		40 MWe	
	Hawaii	Puerto Rico	Hawaii	Puerto Rico
4.4 System Refit, Modification	N/C	N/C	N/C	N/C
4.4.1 Design				
4.4.2 Platform System				
4.4.3 Land-Based Containment System				
4.4.4 Seawater Pipe System				
4.4.5 Power System				
4.4.6 Energy Transfer System				
4.4.7 Energy Utilization System				
4.4.8 System Test and Evaluation				
4.4.9 Deployment Services				
4.5 System Disposal	0.0	0.0	0.0	0.0
4.5.1 Demobilization				
4.5.2 Equipment Disposal				
4.5.3 Facilities Disposal				
4.5.4 Platform Disposal				
4.5.5 Seawater Pipe Disposal				

SECTION IX

ALTERNATIVE PLANT SITING CONCEPTS

In the course of developing conceptual designs for land-based OTEC plants, a few alternative power system siting configurations were envisaged. Though not developed or cost estimated, they appear to have sufficient merit to warrant further study, because a large proportion of construction cost (particularly at the Puerto Rican site) is required for the sea water pipe systems to traverse the shallow water from the power plant to the continental slope. For example, in Puerto Rico the cost of manufacturing and installing the shallow water pipes for a 40 MWe plant is estimated to be \$72 million or 39% of the total. Two alternate plant configurations are suggested for further investigation:

BARGE MOUNTED, BOTTOM SUPPORTED POWER PLANT

A suggested configuration for this alternative is shown in Figure IX-1. The OTEC plant power components could be assembled and tested on board a barge located in an existing ship yard or graving dock in an area where skilled labor and equipment was readily available. Once the power system was operating satisfactorily, it could be towed to the intended site. Meanwhile, a much shorter length of cold water intake pipe could have been installed as described in Section VI. The barge would be floated over the sea water pipe termination and flooded down onto a prepared bed. The sea water pipe systems would then be sealed into the hull. Additional native material back fill could be placed around the barge to insure its survival in storms. The electric power cable to the onshore grid could be layed on the shallow sea floor, or run to shore on a trestle, or suspended from power poles. Where distances from shore to the beginning of deeper water are great this concept may offer a more economical solution than installing long runs of large diameter pipe in shallow water.

Figure IX-1. Barge Mounted, Land-Based OTEC Power Plant

OFFSHORE HEAT EXCHANGERS

Another alternative power plant configuration involves splitting and separating the components of the ammonia cycle: placing the evaporators and condensers offshore at the edge of the continental slope; and the turbines, generators, and power substation on the shore. A suggested configuration for this alternative is shown in Figure IX-2. This concept could also serve to reduce costs by eliminating the long, shallow seawater pipelines. It would require longer ammonia piping runs, however, and the resulting loss in power plant efficiency due to the higher ammonia cycle friction losses may render the concept unfeasible. These losses need to be compared with the cold water seawater system friction losses, and, when considering a floating OTEC plant, to the power losses in the electric transmission cable. A simplified schematic of the envisaged power cycle is shown in Figure IX-3.

The main advantages of this configuration are:

- reduced cost by eliminating three long seawater pipes
- minimal dynamic loading of seawater pipes when compared to those for floating OTEC plants
- eliminating cost and power losses of the offshore power transmission cable when compared to a floating OTEC plant

As shown in Figure IX-2, the heat exchangers could be immersed below an offshore jacket structure of the type used for oil production in the Gulf of Mexico. This jacket would provide vertical access to the heat exchangers for cleaning and maintenance. The ammonia cycle piping could be run above the water on a trestle. If ambient temperature variations caused problems, these lines could be heavily insulated or placed in seafloor trenches where minimal ambient temperature changes would occur. Should the power cycle efficiencies prove sufficient, this is also believed to be a more economical configuration where there are large distances from shore to the beginning of deeper water.

Figure IX-2. Split Ammonia Cycle Configuration

Figure IX-3. Schematic of Split Ammonia Cycle
IX-5