DOE/ET/4063--1 (Vol. 1)

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DOE/ET/4063--1 (Vol.1)

OTEC PLATFORM CONFIGURATION AND

INTEGRATION STUDY –

FINAL REPORT

VOLUME 1

SYSTEMS ENGINEERING

AND INTEGRATION

APRIL 1978   LMSC-D623756

Prepared for

UNITED STATES DEPARTMENT OF ENERGY

DIVISION OF SOLAR ENERGY

Under Contract EG-77-C-01-4063

Prepared by

OCEAN SYSTEMS

LOCKHEED MISSILES & SPACE COMPANY, INC.

A SUBSIDIARY OF LOCKHEED CORPORATION

Supported by

EARL AND WRIGHT   BECHTEL CORPORATION

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FOREWORD

The OTEC Platform Configuration and Integration Study was performed by Lockheed
Missiles & Space Company, Incorporated, under DOE Contract EG-77-C-01-4063.
Supporting Lockheed in this work were six subcontractors: Bechtel Corporation;
Earl & Wright Consulting Engineers; Hydronautics, Incorporated; Morris Guralnick
Associates, Incorporated; Tuned Sphere International, Incorporated; and T.Y. Lin
International.

The final report is comprised of four separately bound volumes, as follows:

Volume 0 EXECUTIVE SUMMARY
Volume 1 SYSTEMS ENGINEERING AND INTEGRATION
   describes the systems integration and evaluation of six OTEC
   platform configurations and recommendations for the most
   satisfactory configuration for an OTEC commercial plant
Volume 2 TECHNICAL CONCEPT
   describes the conceptual designs of two platform configurations
   for a 400-MW(e) (net) commercial plant
Volume 3 PROJECT PLAN
   presents the project plan for an OTEC demonstration plant

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CONTENTS OF REPORT

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CONTENTS OF VOLUME 1

Section 1
INTRODUCTION

The economic success of an Ocean Thermal Energy Conversion (OTEC) system is highly dependent on a platform which provides adequate support for the power system, accommodates reliably the cold water pipe, and is most cost effective. This report presents the results of a study conducted for the Department of Energy to assess six generic types of platforms to determine the most satisfactory platform for several potential sites. The six platform configurations are ship, circular barge, semi-submersible, Tuned Sphere, submersible, and spar. These represent directional and symmetric types of platforms which operate on the surface, at the interface, and submerged. The five sites for this study were primarily New Orleans, Keahole Point (Hawaii), Brazil, and secondarily Key West and Puerto Rico. Electrical transmission of energy by submarine cable is the planned form of energy transmission for all sites except Brazil, where chemical conversion is to be the method of transmission.

Designs based on the six generic platform configurations are illustrated in Fig. 1-1 as arranged for 100-MW(e) (Net) output of the OTEC plant. As a primary design guideline for the cold water system, the discharge of the cold water has been specified to be below the 100-meter depth. The design arrangements shown in this phase of the study have separate discharges of the warm and cold water with the warm water being discharged into the mixed layer relying upon the mean ocean current to effect transport of the discharge to avoid recirculation into the warm water intake. If a mixed (combined warm and cold water) discharge is required, minor revisions will be required to the internal arrangements and an enlarged discharge duct will accommodate this potential requirement.

This study is devoted to the platform (or ocean systems) of the OTEC plant which is chiefly comprised of the hull and structure, the seawater system, the position control system, and miscellaneous support/assembly systems. The principal elements in the work breakdown structure for the commercial plant are presented in Fig. 1-2. The

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Fig. 1-1

PLATFORM CONFIGURATIONS
100MW(e) NET (INTERNAL POWER SYSTEM)

	SHIP	CIRCULAR BARGE	SEMI	TUNED SPHERE	SUB	SPAR
SURFACE						
100 M						
DRAFT / BEAM	0.38	0.32	0.33	0.80	1.41	0.80
WATER- PLANE AREA						
LENGTH / BEAM	2.5	1	1.1	1	2.37	1
DISPLACEMENT / OUTPUT	2.74 TONNES /KW	2.43	3.49	2.82	2.46	3.35
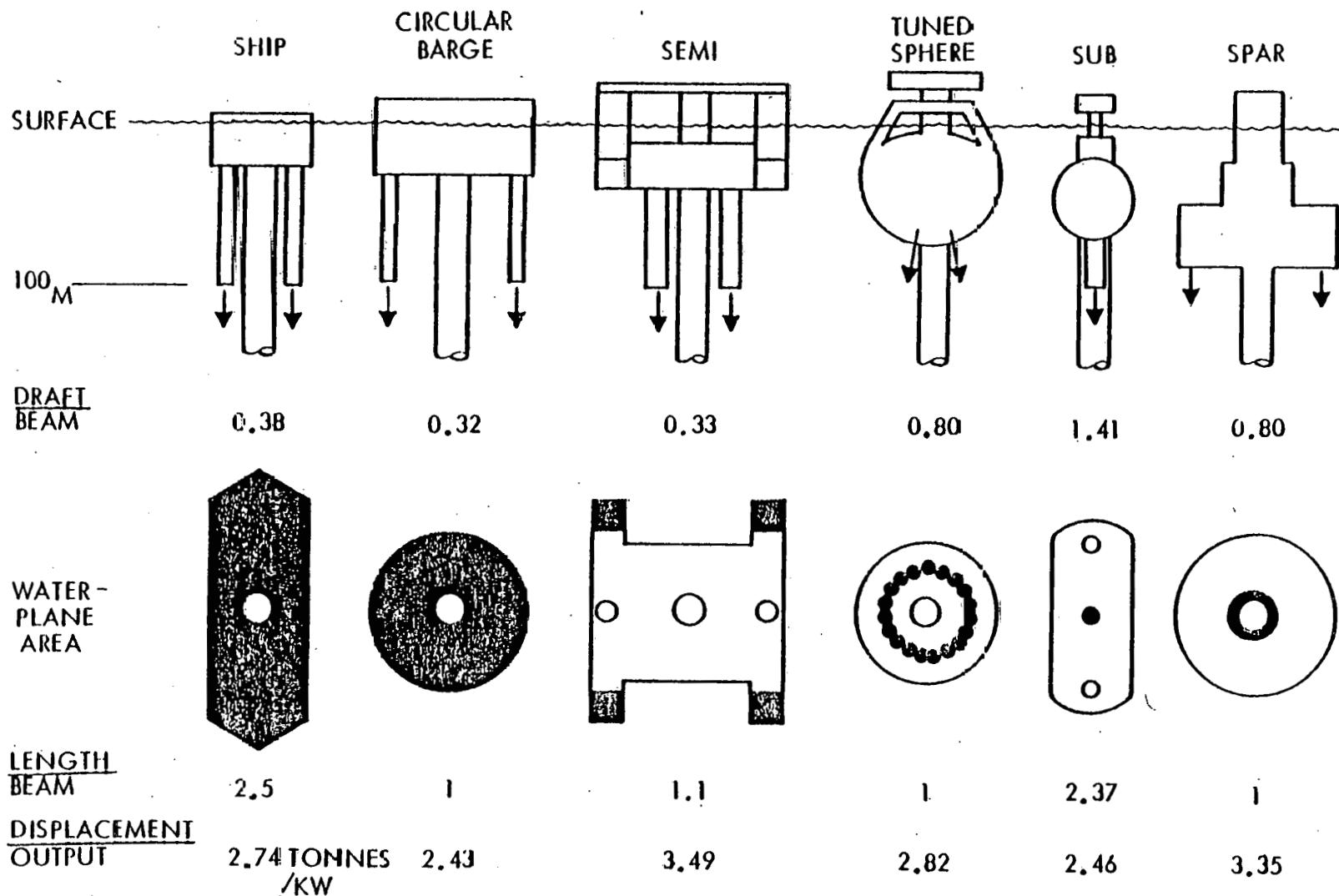
Fig. 1-2

WORK BREAKDOWN STRUCTURE
- MAJOR COMPONENTS
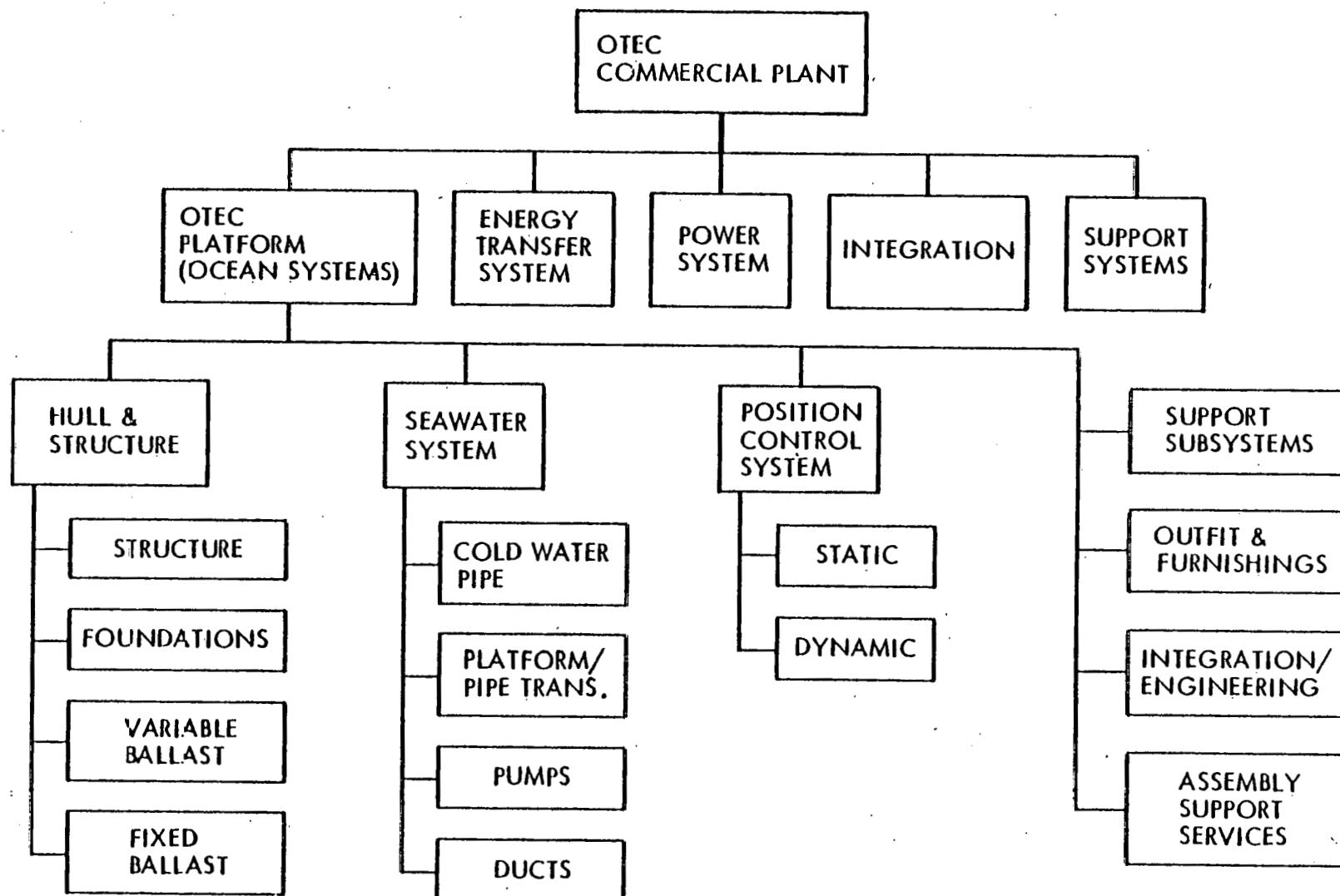
assessment of the six platform configurations was conducted utilizing a baseline plant [100-MW(e) (Net)] and site (New Orleans) with variations from the baseline to cover the range of interested platforms and sites. The functional flow of this approach is shown in Fig. 1-3. The power systems components for this study were defined by DOE and are outlined in Section 2.3.1 of this report.

The requirements for the OTEC platform are detailed in Ref. 1 and are highlighted below:

1. Major components will be constructed in U.S. facilities.
2. Operational life of 40 years at sea shall be projected.
3. The platform must be capable of connection to the electrical transmission system at all times.
4. The maximum watch circle of the platform shall be 5 percent of the water depth.
5. The platform must survive a 100-year storm.
6. The platform must be constructable and operable under prevailing codes and rules.
7. The platform must accommodate a power system and seawater systems.

Section 2 of this report presents the analyses, design, and supporting data for the evaluation of the most satisfactory platforms for the commercial OTEC plant. Section 3 presents a discussion of the effect of the variation in the parameters defining a site on the optimum systems or platform configuration. Section 4 presents an evaluation of the impact of technical advance of the power system on platform evaluations. Section 5 is a summary of project results.

Reference

1. Lockheed Missiles & Space Company, Inc., OTEC Platform Configuration and Integration, Vol. 1 Systems and Requirements Analyses and Vol. 2 System Evaluation Plan, LMSC-D564067-A, Aug 1977

Figure 1-3

APPROACH TO COMMERCIAL PLANT STUDY

REQUIREMENTS

DESIGN GUIDELINES

STUDY PARAMETERS

- 6 PLATFORM TYPES
- 3 (5) SITES
- 4 POWER MODULE SIZES
- 2 ENERGY TRANSFER SYSTEMS
- ATTACHED/DETACHED CWP

BASELINE DEFINED

- 100 MWe (NET)
- HORIZONTAL SHELL & TUBE
- 25 MWe MODULE
- NEW ORLEANS
- ELEC. TRANS.

ARRANGEMENTS OF BASELINE IN 6 PLATFORMS

200 MWe VARIATION

500 MWe VARIATION

ADAPTED FOR CONCRETE HULL CONSTRUCTION

MOTIONS AND CWP LOADS COMPUTED

ARRANGEMENTS PRINCIPLE CHARACTERISTICS WEIGHTS COSTS CONSTRUCTION METHODS

FUNCTIONAL MODEL

COST MODEL

PARAMETRIC DESIGN/COST

EVALUATION FOR 100 MWe (NET) AT NEW ORLEANS

VARIATION OF SITE, SIZE CHANGE

RECOMMENDATIONS

Section 2
OPTIMUM INTEGRATED OTEC COMMERCIAL PLANT SYSTEM

The primary objective of this report is the description and documentation of optimum OTEC commercial plant systems which integrate the several systems and subsystems of the platform and the power system. The most satisfactory component options and the methodology for their selection are described in Section 2.3. The key interface requirements which either drove the selection of components or have been derived for the selected components are presented in Section 2.2. The platform options are defined separately from the other components in Section 2.4. The optimum plant system for the New Orleans site is derived in Section 2.5.

2.1 METHODOLOGY

The large number and range of parameters to be evaluated for the OTEC platforms, sites, power systems, etc., have been addressed by use of a method involving baseline designs (and parameters) and a large data base. These data are available for use in each assessment and for subsequent utilization of the results of this project. The most relevant data is included within Section 2 of this report. Three volumes of appendixes are also included with this report, which presents the entire engineering data trail for each of the component options.

2.2 INTERFACE CONSIDERATIONS

Fundamental to the accomplishment of a system integration is the analysis and design of effective interfaces. Without these the system remains just a collection of major elements. The objective here is to create the system interface requirements which, when satisfied, will assure the creation of a well-integrated system. Because the objective of the OTEC Study is configuration discrimination, or relative evaluation leading to design candidate selection, those requirements which aid in the evaluation process are given special attention. These are called "drivers" and are shown as number 1 priority on Fig. 2-1.

Figure 2-1 presents interface pairs and priorities. The left-hand column lists the major OTEC system elements and their WBS numbers. For purposes of this figure, it is assumed that a given interface requirement is derived from some functional requirement for an element in that column. The headings for the remainder of the

1 - DRIVER* 2 - HIGH PRIORITY BLANK - LOW PRIORITY REQUIREMENT DERIVED FROM:	\[REQUIREMENTS IMPOSED ON:\] HULL & STRUCTURE	SEAWATER SYSTEMS	POSITION CONTROL SYSTEM	SUPPORT SUBSYSTEMS	OUTFIT & FURNISHINGS	POWER SYSTEM	ENERGY TRANSFER SYSTEM	SUPPORT FACILITIES
1.0 HULL & STRUCTURE		1	2			2		1
2.0 SEAWATER SYSTEM	1					2		1
3.0 POSITION CONTROL SYSTEM		2						
4.0 SUPPORT SUBSYSTEMS								
5.0 OUTFIT & FURNISHINGS								
0.3 POWER SYSTEM	1	1	2					
0.2 ENERGY TRANSFER SYSTEM	2	2	2					
7.0 SUPPORT FACILITIES	2	2	2			2	2	

*IMPACTS PLATFORM CONFIGURATION SELECTION.

Fig. 2-1 Interface Pairs and Priorities

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columns are identical to those for the rows; and the boxes at their intersections repre-
sent interfaces between component pairs. If one selected, say, Seawater System, from
the left-hand column and Power System from the column headings, the box at their
intersection represents those interfaces for which the requirement is derived from
Seawater System and is imposed on the Power System. Those boxes, cross-hatched
and containing a number 1, are considered to be interface drivers; those containing a
2, high-priority interfaces but not drivers, and the remainder are of minor importance.
A discussion on the platform impact of each of the interface requirement drivers is
presented below.

2.2.1 CWP-Hull Interface Requirement

A requirement for the CWP-Hull interface is to provide an adequate attachment for the
CWP. In order to properly define this interface, it is necessary to determine the mo-
tions to which it is subjected and the bending stress. The hull motion data are presented
in Table 2-1. They represent extreme weather motions (wave height = 58.1 ft) for a

Table 2-1
HULL MOTIONS AFFECTING CWP (58-FT WAVE)

	Ship	Barge	Semi	Tuned Sphere	Sub	Spar
Significant Amplitude						
Heave Motion (m)	9.8	12.3	3.9	0.9	3.4	2.5
Heave Acceleration (m/sec^2)	3.1	2.2	0.9	1.2	1.0	0.6
Surge Motion (m)	4.5	5.1	3.5	3.8	2.9	2.7
Roll/Pitch Motion (deg)	14.8	12.5	3.5	5.7	10.5	2.5
Max. Bending Moment (lb-ft $\times 10^{-9}$)*	0.9	1.5	0.8	1.0	0.9	1.2

*For an effective CWP modulus of 0.3×10^6 psi.

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100-MW(e) plant. For this plant size the CWP submerged will weigh 25,000 long tons (assuming concrete) and will have a 58 ft outside diameter. A steel pipe would weigh approximately half the concrete pipe weight.

The effectiveness of the CWP-Hull interface as a configuration discriminator is quite apparent from a cursory review of the data. In summary, the platform motions and consequent bending moment at the interface is high for surface platforms (ship and barge). Although pitch motion for the ship is a minimal value, roll will not be. Other factors which should be considered in the evaluation of the impact of the interface include the material employed in construction and the high cost which would be incurred through development and implementation of the complex attachment which would be required to isolate the CWP from the plant motions.

Although presented in greater detail elsewhere in the report, it may be of interest to look at an example CWP-Hull interface to achieve a clearer picture of what may be involved. Figure 2-2 shows a simple sketch of a relatively simple attachment
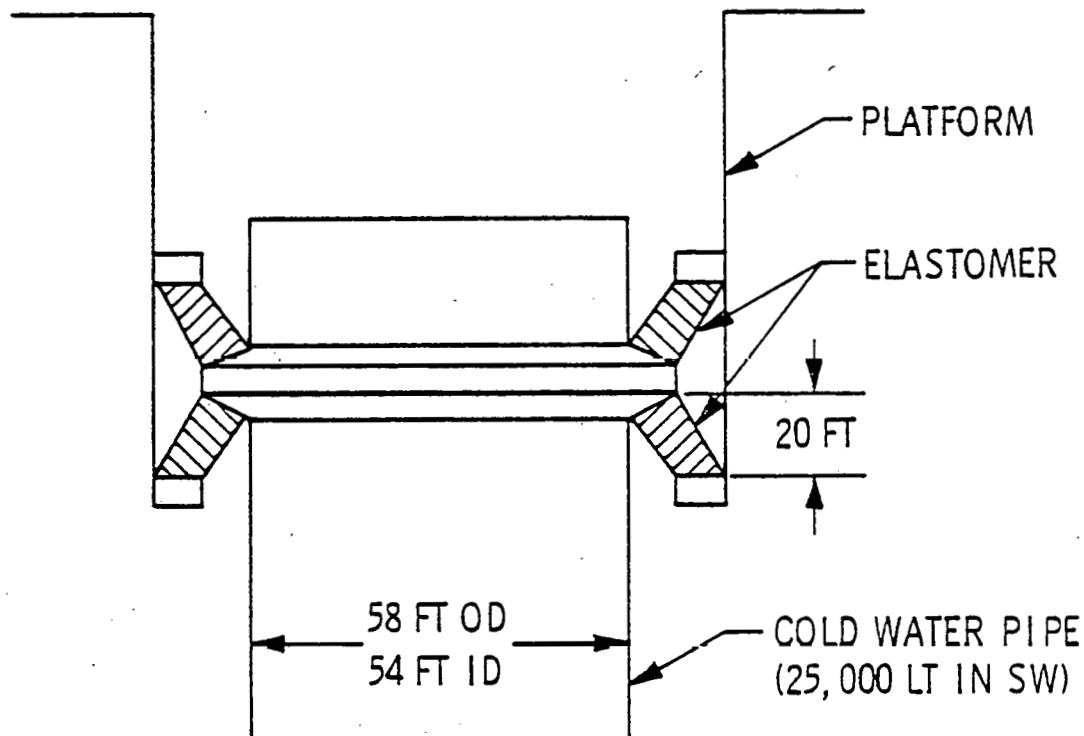
Fig. 2-2 CWP – Platform Interface

consisting of 20-ft rings of stiff elastomer. Such an attachment will minimize angular motion but will have little effect on heave.

2.2.2 CWP/Support-Facilities Interface Requirement

A requirement for the CWP Support Facilities interface is to provide adequate means for physical handling of the CWP during on-site deployment. To define this interface it is necessary to know the weight of the CWP (58,000 LT for the 100 MW(e) plant and 245,000 LT for the 500 MW(e) plant assuming concrete and the external diameter (58 ft for the 100-MW(e) plant and 115 ft for the 500-MW(e) plant). Because of the great weight of the CWP, it must be lifted and lowered into the platform hull in sections. One of the largest operational cranes is the ODIN derrick ship, the dimensions and lifting capacity of which are presented in Table 2-2. Assuming a lift of 2,000 LT per CWP section, some 30 lifts will be required to deploy the pipe for the 100-MW(e) plant. These operations will be affected by the overall height of the platform, which determines the depth to which each section of pipe must be lowered and even assuming that all platform configurations are surfaced during CWP deployment. Hull heights are presented in Table 2-3. Based on these data it is concluded that the surface platforms will present a less difficult CWP handling problem.

If the platform is designed to allow the CWP to be floated into place, the facilities interface problem just discussed is no longer a major concern. Hull designs providing an opening large enough to admit the CWP floated vertically have not been examined sufficiently to incorporate into this document but should be considered for inclusion in the next phase of the study.

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Table 2-2

ODIN DERRICK SHIP

BARGE PRINCIPAL DIMENSIONS

LENGTH OVERALL _____ 178.45 m _____ (585 FT - 6 IN)

LENGTH BETWEEN P.P. _____ 174.75 m _____ (573 FT - 4 IN)

BREADTH _____ 42.70 m _____ (140 FT - 1-1/8 IN)

DEPTH _____ 16.48 m _____ (54 FT - 1-3/16 IN)

DRAUGHT _____ 12.00 m _____ (39 FT - 4-1/2 IN)

CRANE LIFTING CAPACITY

MAINHOIST FIXED CRANE 2680 LT AT _____ 80 FT - 105 FT

MAINHOIST REVOLVING CRANE 2410 LT _____ 80 FT - 105 FT

Table 2-3

PLATFORM HEIGHT (M)

Plant	100 MW(e)	200 MW(e)	500 MW(e)
Ship	32	32	56
Barge	43	50	105
Semi	65	65	105
Tuned Sphere	55	71	
Sub	49	49	110
Spar	105	110	120

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2.2.3 Hull/Support-Facilities Interface Requirement

A similar requirement to that discussed just previously is imposed on the Manufacturing Support Facilities by the Hull. In order to define this interface it is necessary, as a minimum, to establish maximum and minimum Hull dimensions. These are presented in Table 2-4 for both the 100-MW(e) and 500-MW(e) plants. Because of the Government

Table 2-4

HULL SIZE DATA

Item	Ship	Barge	Semi	Tuned Sphere	Sub	Spar
100 MW(e)						
Max Dim (m)	165	98	132	91	116	100
Min Dim (m)	66	98	120	91	49	100
500 MW(e)						
Max Dim (m)	356	149	216	175	335	156
Min Dim (m)	82	149	162	175	119	156

imposed restriction to use of only U.S. manufacturing facilities, there is an incompatibility between platform size and available facilities. The largest U.S. construction facility is the General Dynamics, Quincy Division graving dock at Quincy, Massachusetts. This graving dock is actually two docks which, when the separator between them is removed, opens up into a large facility of 267 m × 91 m × 7 m.

A comparison with the data of Table 2-4 shows that the barge, semi-submersible, and spar 100-MW(e) configurations cannot fit into the dock area without some form of modularization. Alternatively, these platforms could conceivably be constructed in stages or constructed on site. A look at the 500-MW(e) size data demonstrates the incompatibility of all configurations with the graving dock and the consequent necessity

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for modularization; or, as suggested for the 100-MW(e) plants, constructed in stages or on site. Another alternative, of course, is the construction of a new and larger facility at an increased capital cost for the platform.*

2.2.4 Power-System/Hull Interface Requirement (Motions)

Two Power System — Hull interface requirements are discussed. The first, addressed in this section, is concerned with the effect of hull motions on the performance of the heat exchangers. The second, discussed in the next section, is concerned with the availability of equipment laydown space and access through the hull to the heat exchangers sufficient to allow their removal.

Regarding the impact of hull motions on the Power System heat exchangers, it has been estimated (and is being verified) that 3° - 5° of angular motion will cause the heat exchangers to reach their acceptable limit in degradation of performance. No comparable limit has been established for heave acceleration. Hull motions are presented demonstrating the effect of 58 ft and 20 ft waves on 100-MW(e) platforms in Table 2-5.

Table 2-5
HULL MOTIONS AFFECTING HEAT EXCHANGERS

	SHIP	BARGE	SEMI	TUNED SPHERE	SUB	SPAR
ANGULAR MOTION (°)						
58 FT WAVE	14.8	12.5	3.5	5.7	10.5	2.5
20 FT WAVE	2.2	1.9	0.7	0.5	0.7	0.3
HEAVE ACCEL (M/SEC^2)						
58 FT WAVE	3.1	2.2	0.9	1.2	1.0	0.6
20 FT WAVE	0.6	0.5	0.2	0.3	0.2	0.1
ALLOWABLE LIMIT ON HX						
AVE. MOTION (°)	BEST ESTIMATE AT PRESENT IS 3° TO 5°					
ACCEL. OF GRAVITY	0.1 G • 3.2 FT/SEC^2 • 1.0 M/SEC^2					

*A larger graving dock, capable of handling all plant sizes discussed in this report is being constructed at Jacksonville, Florida for Off-Shore Power Systems. Its dimensions will be: Length - 5300 ft and width - 550 ft.

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From the data presented it is readily observed that, for the 58-ft extreme seas wave, the ship and barge configuration motions exceed the estimated maximum allowable. For the 20-ft wave, the situation improves dramatically, but the barge motions remain only marginally acceptable. An identical situation exists in heave, although the seriousness of the heaving of surface platforms on the heat exchanger is unknown. Decoupling of the hull from the heat exchangers to minimize motions of the latter would require highly complex support foundation which would prove quite costly.

2.2.5 Power-System/Hull Interface Requirement (Maintenance)

The interface requirement imposed on the Hull by the Power System is for adequate laydown area for elements such as the turbogenerator cover and access through the Hull to the heat exchangers to allow their removal for refurbishment or replacement. The minimum laydown area requirement and the minimum access diameters for 5, 8, 12-1/2, and 25 MW(e) heat exchangers is presented in Table 2-6.

Table 2-6

LAYDOWN AND ACCESS AREAS

Item	1-5 MW	1-8 MW	1-12-1/2 MW	1-25 MW
Power System HX's				
Min Laydown Area (Ft)^2	40 × 9	50 × 11	64 × 12	92 × 12
Min HX Access Diam (Ft)	22	26	30	38

It may be of interest to note that access diameters for removal of a complete 25-MW(e) Power System unit would vary from 160 to 80 ft, the former relating to a five-5-MW(e) heat exchanger package and the latter to a one-25-MW(e) package. These values are so large and their respective weights so great ($\approx$ 5000 LT's) that no serious consideration has been given to these access areas.

If it is possible to use the same laydown area for several 5-MW(e) heat exchangers this could be a substantial plus for their use over larger heat exchanger sizes.

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Similarly, if the same access area can be employed to extract several 5-MW(e) heat exchangers, again this size may be a better choice than a larger one. Conversely, where complex 5-MW(e) heat exchanger arrangements are required, maintenance will be difficult and the larger heat exchanger sizes may be advantageous.

It is probably unnecessary to comment that the employment of external detachable module heat exchangers would largely eliminate this interface problem.

2.3 MOST SATISFACTORY COMPONENT OPTIONS

The preferred OTEC plant configuration will be that one which combines the best features of all systems and subsystems in package which is most viable from a cost, risk, and schedule standpoint. At this stage in the design process it is essential to identify the several most reasonable alternatives for each system and to set a measure of importance on the system or on the alternatives. A high cost system may have high and low risk alternatives, and may have only a small range of cost variation among the alternatives. From this activity will spring messages to the designer, the planner, the analyst, and the interface coordinator. The purpose of this Section is to present these alternatives for the OTEC commercial plant, to present quantified statements about the alternatives, and to recommend options for components to be used in the comparative assessment of six platform types. Later Sections (3 and 4) examine the effects of variations in some of the most important of these components as they affect the evaluation of the most satisfactory OTEC commercial plants for five potential sites and two forward energy transmissions (electrical transmission and chemical production, NH_3).

2.3.1 Power System

This section summarizes the Power System sizing data furnished to the naval architects for their use in configuration pre-conceptual design. It includes volume and weight requirements and general arrangements for 5, 8, 12-1/2, and 25 MW(e) internal horizontal and vertical heat exchangers along with alternative concepts for external detachable power modules. Estimates of laydown areas in access areas for Power System maintenance and repair are presented in Section 2.2.

The detachable module is given special attention in Section 2.3.1.2 because of the following attributes:

- It serves to eliminate large internal areas and volumes required for maintenance and replacement of internal components.

- It eliminates the need for large crane lifting capacity.

- Water boxes can be eliminated through selection of external detachable modules.

- It provides for ease of module installation and replacement.

- A marked reduction in size and cost of the Spar platform is possible employing detachable modules.

2.3.1.1 Baseline Power System. The baseline Power System is a 25-MW(e) module made up of 5, 8, 12-1/2, or 25 MW(e) horizontal heat exchangers, internally mounted (shirtsleeve environment). The sizing and cost data for both these and the vertical heat exchangers were developed by Gilbert Associates and furnished to Lockheed by the Government. (See Refs. (1) and (2).) These data have been reworked into a usable form for use by the naval architects and are presented in Table 2-7. Note that vertical heat exchanger data are also included in this table.

Whether made up of 5, 8, 12-1/2, or 25 MW(e) heat exchanger sub-modules, the ultimate package will be a 25 MW(e) Power System packaged module. These modules were developed as Power System envelopes by Lockheed and furnished to the naval architects

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as package volumes for incorporation into their platform configuration pre-conceptual designs. Sketches leading to specification of packaged module envelopes are presented in Figs. 2-3, 2-4, 2-5 and 2-6, and 2-7 and 2-8 for the 25-MW(e) modules made

of 5, 8, 12-1/2, and 25 MW(e) sub-modules, respectively. Two arrangements of the 12-1/2 and 25 MW(e) sub-modules were layed out to determine which of the alternatives was best adapted to a given platform configuration.

Based on the data presented in Table 2-7 and the package envelopes presented in the figures just discussed, total areas, volumes, and costs were generated for 25-MW(e) modules and for packaged modules. See Tables 2-8, 2-9, 2-10 and 2-11 which present these data for 5, 8, 12-1/2, and 25 MW(e) sub-modules, respectively.

Table 2-7

POWER SYSTEM COMPONENTS SIZE AND COST

| | MODULE OUTPUT, MW(e) | | OD (FT) | LENGTH (FT) | WIDTH (FT) | HEIGHT (FT) | DRY WEIGHT | | WET WEIGHT | | WET WT/AREA (LB/FT^2) | WET WT/VOL (LB/FT^3) | UNITS REQUIRED | TOTAL COST (10^4 DOLLAR) |
	NET	GROSS					LT	10^4 LBS	LT	10^4 LBS				
AMMONIA PIPING (VAPOR)	5	6.5	5.3	45			38.6	8.65	38.8	8.7		87.6	1	
	8	10.4	8.0	50			36.7	8.22	37.2	8.3		33.0	1	
	12.5	16.3	9.6	50			36.0	8.06	36.7	8.2		23.0	1	
	25	32.5	10.0	60			35.3	7.91	36.1	8.1		17.2	1	
AMMONIA PIPING (LIQUID)	5	6.5	3.2	45			26.8	6.00	33.0	7.4		204.4	1	6.7
	8	10.4	6.0	50			25.8	5.78	50	11.2		79.2	1	7.5
	12.5	16.3	7.7	50			24.0	5.38	64	14.4		61.9	1	8.0
	25	32.5	8.0	60			21.3	4.77	73	16.4		54.4	1	5.8
AMMONIA PIPING (MISC)	5	6.5					4.5	1.0	4.5	1.0				
	8	10.4					5.4	1.2	5.4	1.2				
	12.5	16.3					5.4	1.2	5.4	1.2				
	25	32.5					4.5	1.0	4.5	1.0				
AMMONIA COMPRESSOR	5	6.5												
	8	10.4												
	12.5	16.3												
160 HP	25	32.5		5.5	18	4	8.93	2.0	8.9	2.0	202	50.5	1	4.0
AMMONIA STORAGE TANK	5	6.5												
	8	10.4												
	12.5	16.3												
	25	32.5	10	35			16.07	3.6	40.2	9.0		2.1	16	66
AMMONIA FEED PUMP														
460 HP	5	6.5	5.0	11.0			5.4	1.21	5.4	1.2	611	55.6	2	35
810 HP	8	10.4	5.5	11.5			8.3	1.86	8.3	1.9	800	69.5	2	35
1340 HP	12.5	16.3	6.5	13.5			10.7	2.40	10.7	2.4	723	53.6	2	56.5
2390 HP	25	32.5	7.0	13.0			12.4	2.78	12.4	2.8	728	56.0	2	35
AMMONIA VACUUM PUMP				5	6	7	3.6	0.8	3.6	0.8	267	38.1	1	3
DEMISTER	5	6.5	16	43		43	40.6	9.1	42.3	9.5		11	1	60
	8	10.4	16	43		43	40.6	9.1	42.3	9.5		11	2	120
	12.5	16.3	16	43		43	40.6	9.1	42.3	9.5		11	3	180
	25	32.5	16	43		43	40.6	9.1	42.3	9.5		11	5	300
TURBO-GENERATOR	5	6.5		40	9	8	49	11.0	49	11.0		34.0	1	70
	8	10.4		50	11.4	10	81	18.1	81	18.1		27.9	1	106
	12.5	16.3		64	12	12	123	27.6	123	27.6		30.0	1	185
	25	32.5		92	12	12	202	45.3	202	45.3		34.2	1	320
HORIZONTAL SHELL & TUBE HEAT EXCHANGER WITH WATERBOXES (BASELINE)	5	6.5	22.1	59.6	22.1	22.1	406	91	674	151				
	8	10.4	25.8	69.7	25.8	25.8	652	146	1,080	242	1,346	66.4	2	
	12.5	16.3	30.0	80.9	30.0	30.0	1,018	228	1,692	379	1,562	66.4	2	
	25	32.5	37.7	102	37.7	37.7	2,031	455	3,371	755	1,964	66.4	2	
VERTICAL SHELL & TUBE HEAT EXCHANGER WITH WATERBOXES	5	6.5	22.2	22.2	46.6	46.6	168	37.7	280	62.6	1,617	34.8	2	
	8	10.4	26.0	26.0	54.5	54.5	269	60.3	447	100.1	1,885	34.8	2	
	12.5	16.3	30.1	30.1	63.3	63.3	422	94.5	701	157	2,080	34.8	2	
	25	32.5	37.9	37.9	79.6	79.6	844	189	1,397	313	2,774	34.8	2	

LEGEND:

P = AMMONIA FEED PUMP

S = NH$_3$ STORAGE TANK

C = CONDENSER, 5 MW(e)

D = DEMISTER, 5 MW(e)

E = EVAPORATOR, 5 MW(e)

T = TURBOGENERATOR, 5 MW(e)

60 FT

157 FT

SCALE: 1 IN = 40 FT

118 FT

NOTE: 16 NH$_3$ STORAGE TANKS REQD;
NOT SHOWN IN ALL VIEWS
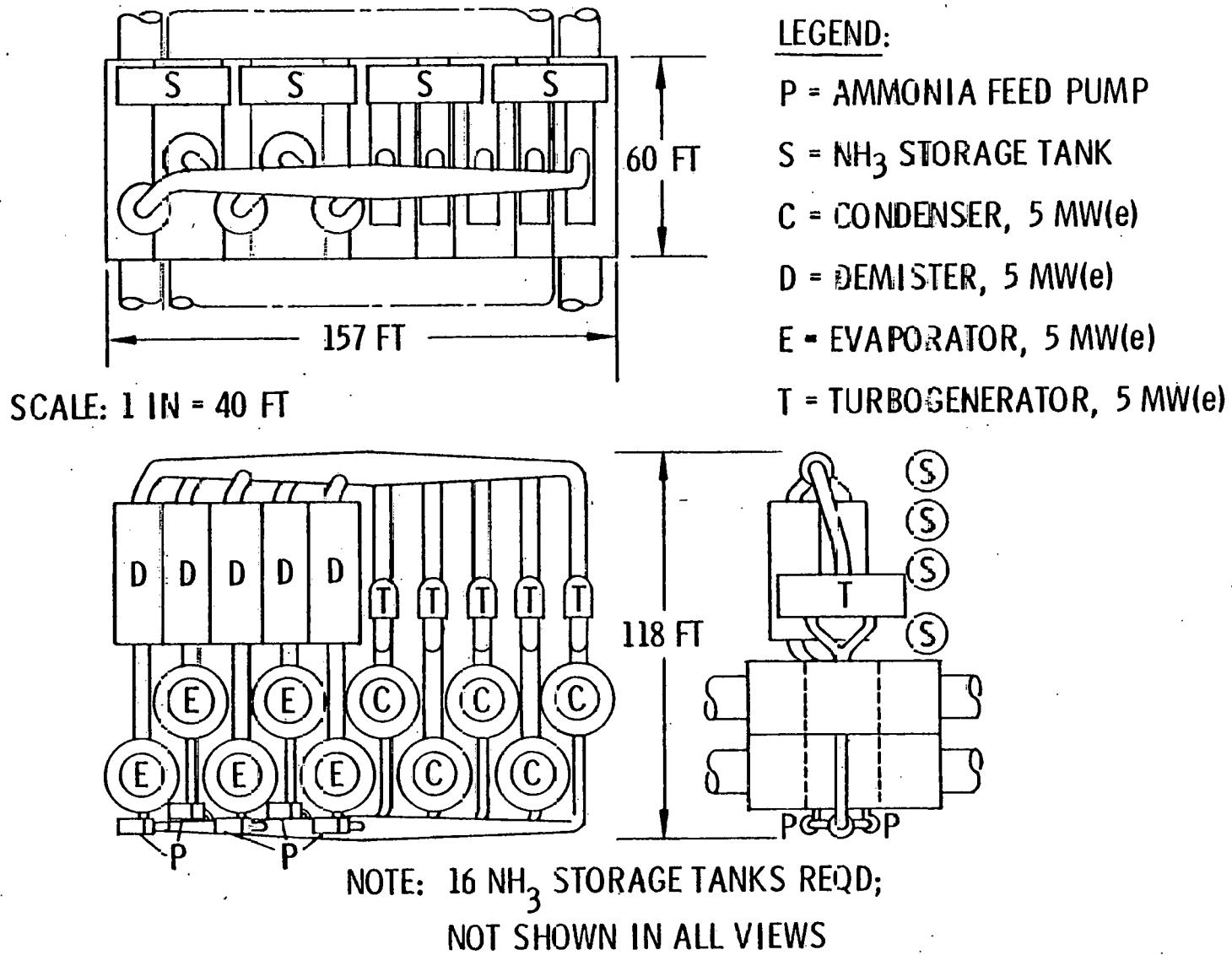
Fig. 2-3 Packaged 25-MW(e) Net Power System. Units are 5-MW(e) net
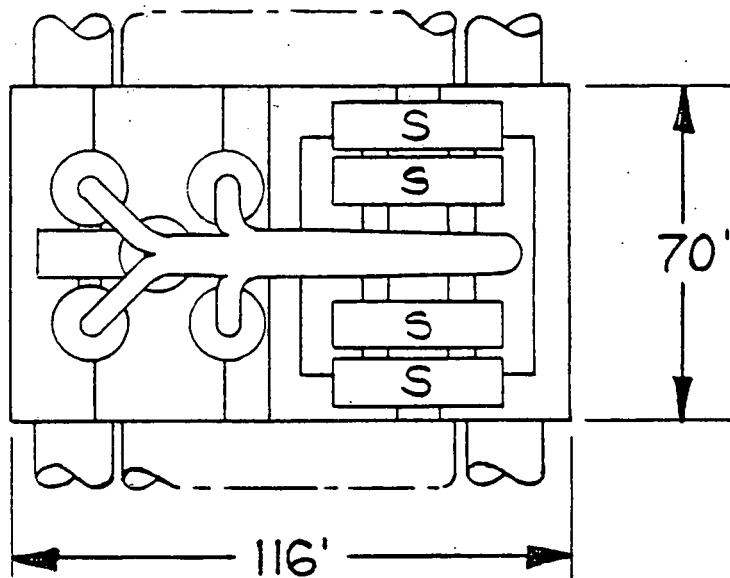
SCALE : 1" = 40'

LEGEND:

P = AMMONIA FEED PUMP
S = NH₃ STORAGE TANK
C = CONDENSER, 8 MWₑ
D = DEMISTER, 5 MWₑ
E = EVAPORATOR, 8 MWₑ
T = TURBOGENERATOR, 8 MWₑ
M = MANIFOLD

70'

116'

144'
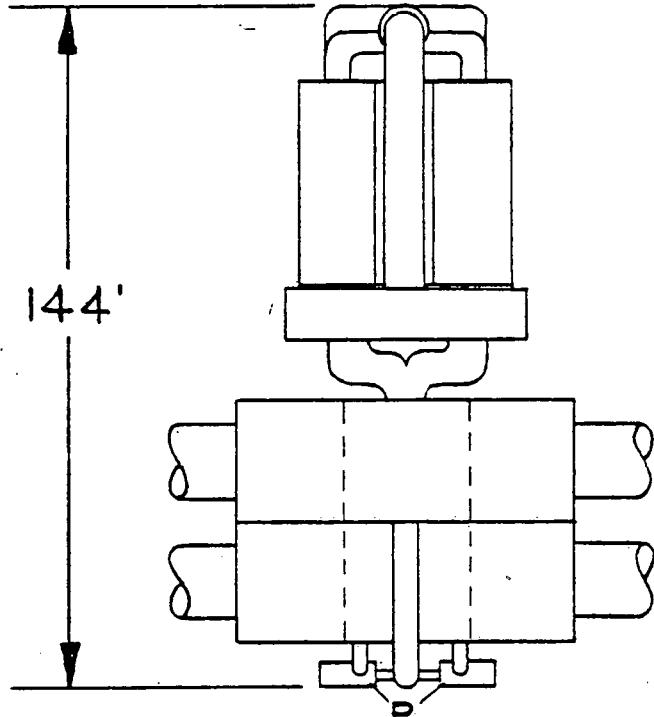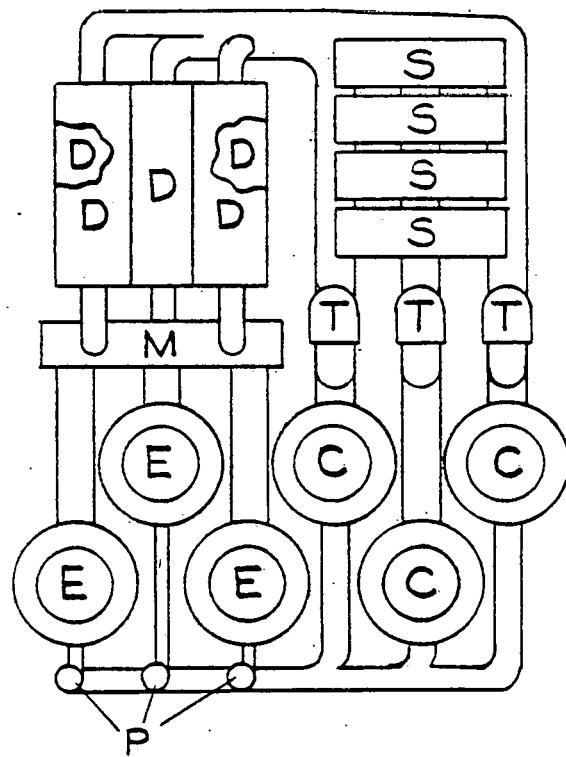
NOTE : 16 NH₃ STORAGE TANKS REQ'D,
NOT SHOWN IN ALL VIEWS.

Fig. 2-4 Packaged 25-MW(e) Net Power System. Units are 8 MW(e) net

2-17

SCALE : 1" = 40'

LEGEND :
P = AMMONIA FEED PUMP
S = NH₃ STORAGE TANK
C = CONDENSER, 12.5 MWe
D = DEMISTER, 5 MWe
E = EVAPORATOR, 12.5 MWe
T = TURBOGENERATOR, 12.5 MWe
M = MANIFOLD

123'

126'

81'
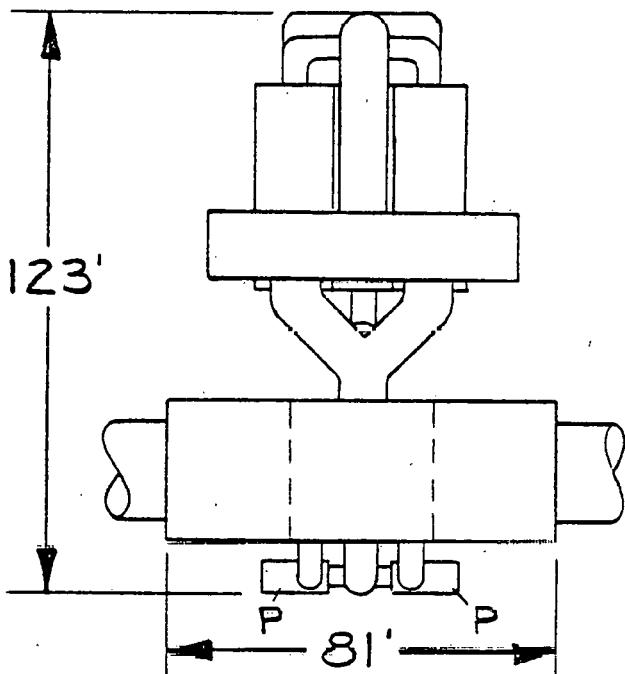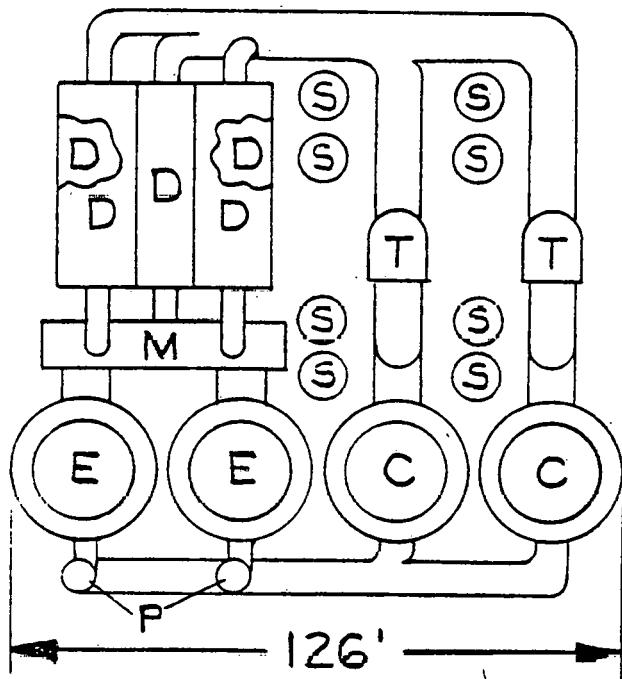
NOTE : 16 NH₃ STORAGE TANKS REQ'D,
NOT SHOWN IN ALL VIEWS.

Fig. 2-5 Packaged 25-MW(e) Net Power System. Units are 12-1/2 MW(e) net

2-18
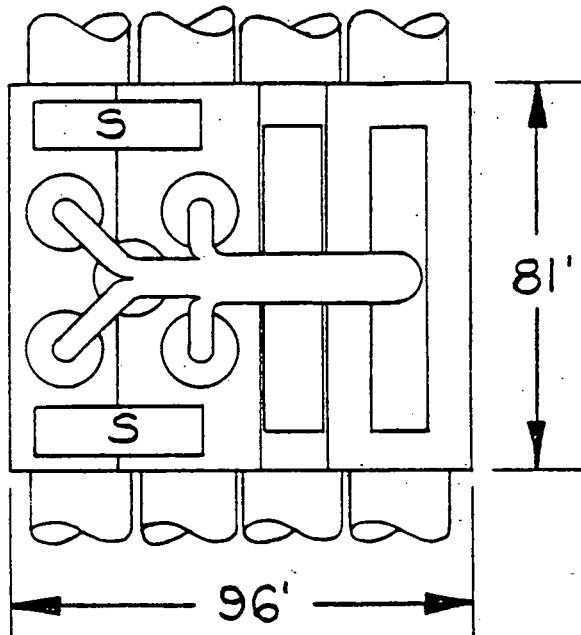
SCALE : 1" = 40'

LEGEND:

C = CONDENSER, 12.5 MWe
D = DEMISTER, 5 MWe
E = EVAPORATOR, 12.5 MWe
M = MANIFOLD
P = AMMONIA FEED PUMP
S = NH₃ STORAGE TANK
T = TURBOGENERATOR, 12.5 MWe

81'

96'

146'
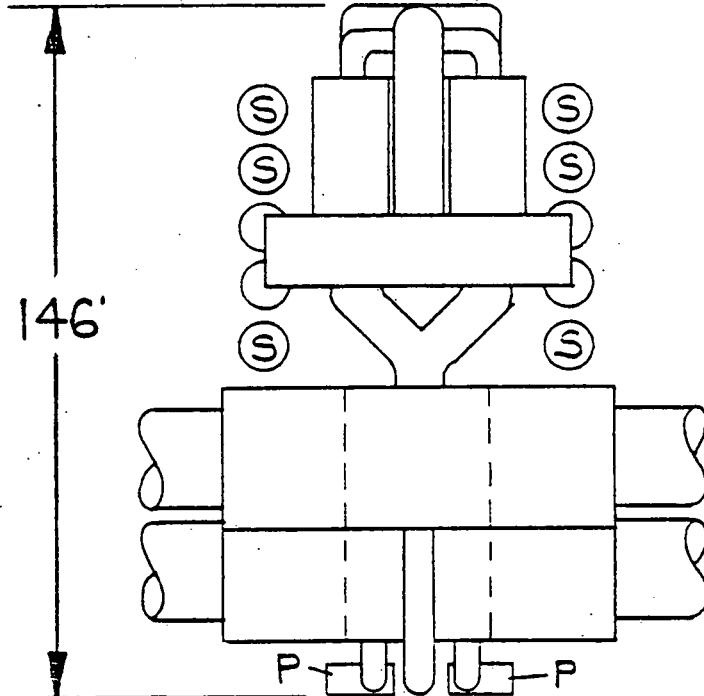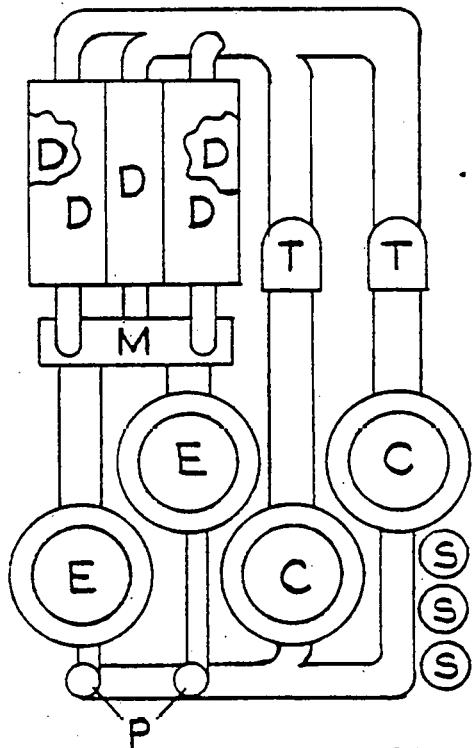
NOTE: 16 NH₃ STORAGE TANKS REQ'D,
NOT FULLY SHOWN IN ALL VIEWS.

Fig. 2-6 Packaged 25-MW(e) Net Power System. Units are 12-1/2 MW(e) net
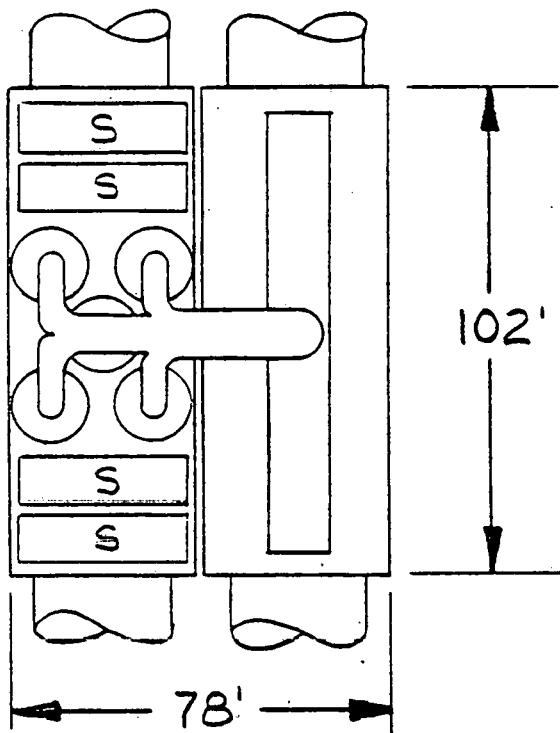
SCALE : 1" = 40'

LEGEND:

C = CONDENSER , 25 MW$_e$
D = DEMISTER, 5 MW$_e$
E = EVAPORATOR, 25 MW$_e$
T = TURBOGENERATOR, 25 MW$_e$
P = AMMONIA FEED PUMP
S = NH$_3$ STORAGE TANK
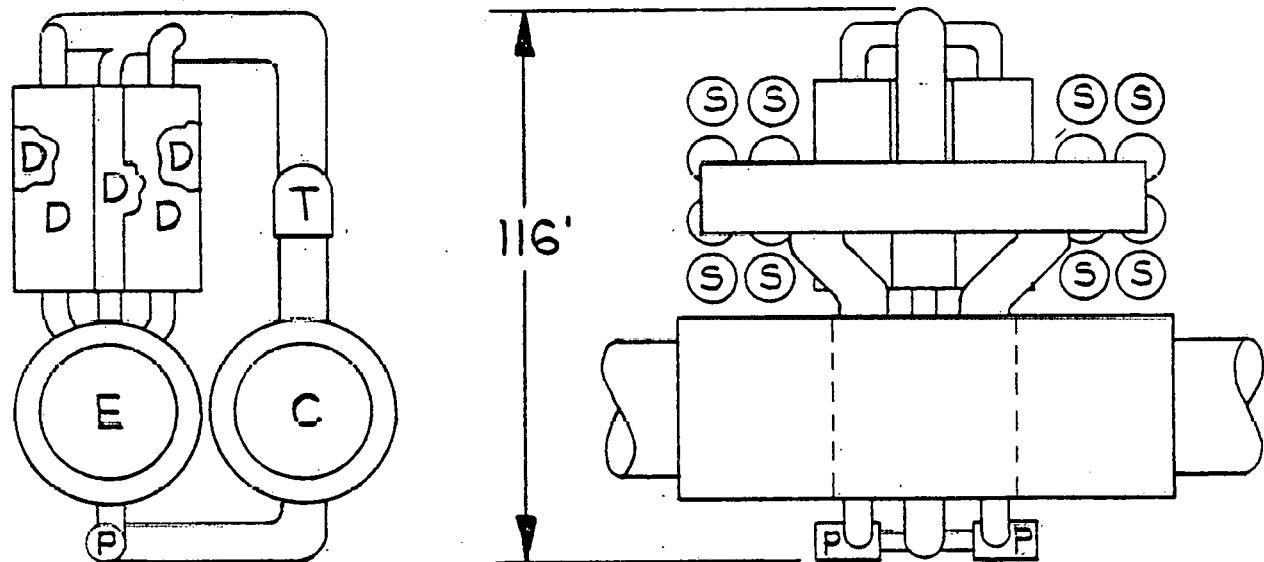
NOTE: 16 NH$_3$ STORAGE TANKS REQ'D,
NOT SHOWN IN ALL VIEWS.

Fig. 2-7 Packaged 25-MW(e) Net Power System. Units are 25 MW(e) net

2-20

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# LEGEND:
C = CONDENSER, 25 MWe
D = DEMISTER, 5 MWe
E = EVAPORATOR, 25 MWe
T = TURBOGENERATOR, 25 MWe
P = AMMONIA FEED PUMP
S = NH₃ STORAGE TANK

SCALE: 1" = 40'

59'

102'

146'

D

T

C

S
S
S
S
S

P

E

P   P
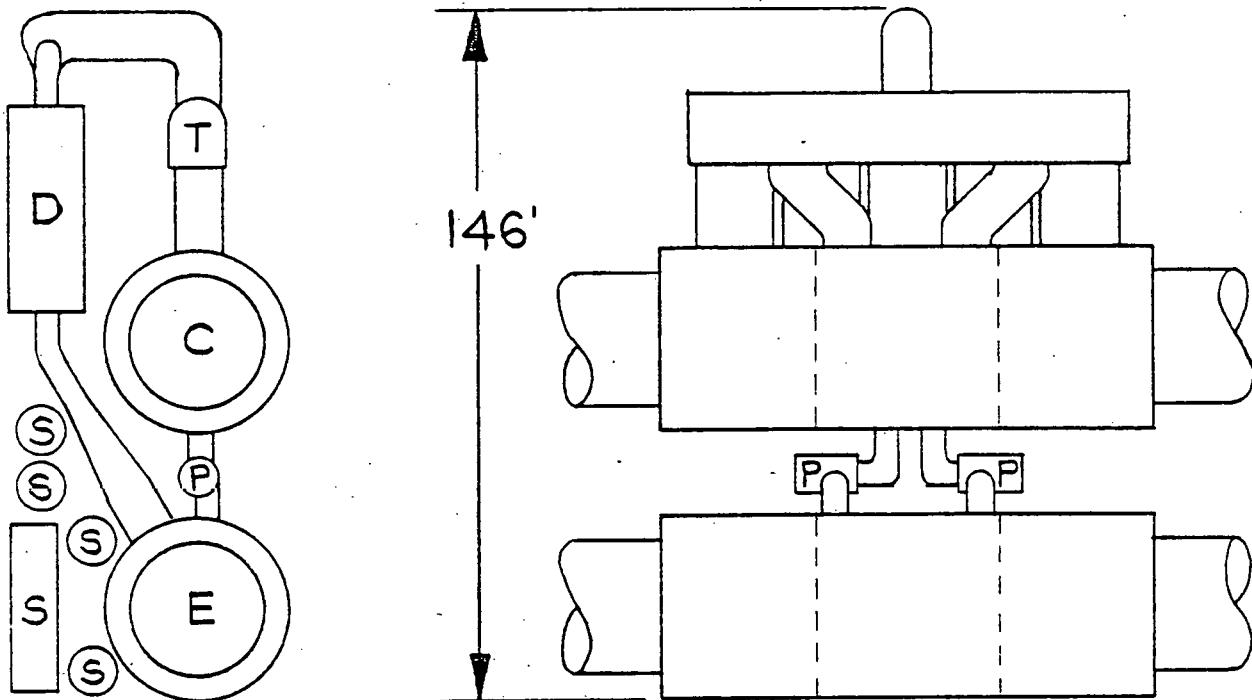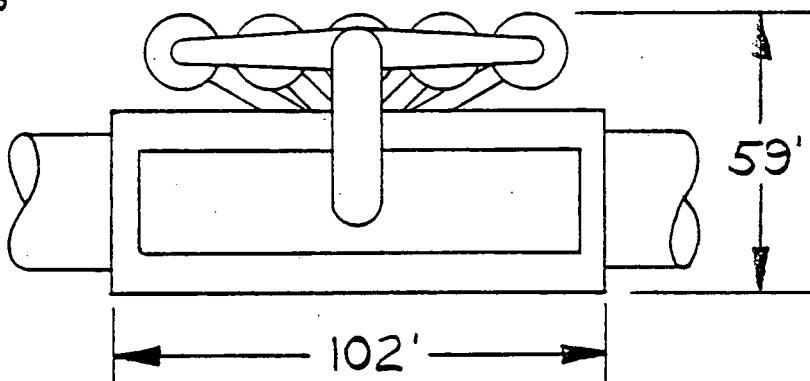
NOTE: 16 NH₃ STORAGE TANKS REQ'D, NOT SHOWN IN ALL VIEWS.

Fig. 2-8 Packaged 25-MW(e) Net Power System. Units are 25 MW(e) net

Table 2-8

CHARACTERISTICS OF POWER SYSTEM MODULE — 5-MW(e) NET, INTERNALLY MOUNTED
CONVENTIONAL HORIZONTAL SHELL/TUBE HEAT EXCHANGERS

| Components	Dry Wt.	Wet Wt.	Deck Area	Volume	Cost	No. Units/ Module
Submodule Components						
HX s	812 LT	1,348 LT	2,634 ft^2	58,218 ft^3	$ 1,875K	2
TG	49 LT	49 LT	320 ft^2	2,560 ft^3	700K	1
NH$_3$ Vapor Assembly	41 LT	41 LT	688 ft^2	11,008 ft^3	600K	1
NH$_3$ Condensate Pumps	11 LT	11 LT	110 ft^2	550 ft^3	350K	2
Submodule Totals	913 LT	1,449 LT	3,752 ft^2	72,336 ft^3	$ 3,525K	
All Submodule Components Per 25 MW(e) Module	4,565 LT	7,245 LT	18,760 ft^2	361,680 ft^3	$17,625K	
Module Components						
NH$_3$ Vapor Piping	38.2 LT	38 LT	239 ft^2	1,264 ft^3	$ 67K	1
NH$_3$ Liquid Piping	26.8 LT	27 LT	144 ft^2	461 ft^3	—	1
NH$_3$ Miscellaneous	6.0 LT	6 LT	—	—	—	1
NH$_3$ Compressor	8.9 LT	9 LT	99 ft^2	396 ft^3	$ 40K	1
NH$_3$ Storage Tanks	257.1 LT	643 LT	5,600 ft^2	56,000 ft^3	$ 660K	16
Module Components Totals	337 LT	723 LT	6,082 ft^2	58,121 ft^3	$ 767K	
All Components Per 25 MW(e) Module	4,902 LT	7,968 LT	24,842 ft^2	419,801 ft^3	$18,292K	
Same in SI Units	4.88 x 10^7 N	7.94 x 10^7 N	2,308 m^2	11,889 m^3	$18,392K	
Per Unit Deck Area	0.197 LT/ft^2	0.321 LT/ft^2	—	—	$730/ft^2	
Per Unit Volume	0.0117 LT/ft^3	0.0190 LT/ft^3	—	—	$43.2/ft^3	
Same in lb/ft^3	26.2 lb/ft^3	42.56 lb/ft^3	—	—	—	
Per MW(e)	196 LT/MW	319 LT/MW	994 ft^2/MW	16,792 ft^3/MW	$736K/MW	
Packaged Module (L=157; W=60; H=118) ft	4,902 LT	7,968 LT	9,420 ft^2	1,111,560 ft^3	$18,392K	
Total/Packaged Module Per MW(e) (for 25 MW(e) Module)	196 LT/MW	319 LT/MW	337 ft^2/MW	44,462 ft^3/MW	$736K/MW	
Per Unit Volume	0.0042 LT/ft^3	0.0068 LT/ft^3	—	—	$15.7/ft^3	
Same in lb/ft^3	9.4 lb/ft^3	15.2 lb/ft^3	—	—	$15.7/ft^3	
Packing Factor = $\frac{PKGE}{COMPS}$	—	—	37.9%	265%	—	

Table 2-9

CHARACTERISTICS OF POWER SYSTEM MODULE – 8-MW(e) NET INTERNALLY MOUNTED CONVENTIONAL HORIZONTAL SHELL/TUBE HEAT EXCHANGERS

Components	Dry Wt.	Wet Wt.	Deck Area	Volume	Cost	No. Units/ Module
Submodule Components						
HXs	1,304 LT	2,160 LT	3,596 ft^2	92,790 ft^3	$ 3,008K	2
TG	81 LT	81 LT	500 ft^2	5,000 ft^3	1,060K	1
NH$_3$ Vapor Assembly	81 LT	81 LT	1,376 ft^2	22,016 ft^3	1,200K	2
NH$_3$ Condensate Pumps	17 LT	17 LT	127 ft^2	696 ft^3	350K	2
Submodule Totals	1,483 LT	2,339 LT	5,599 ft^2	120,502 ft^3	$ 5,618K	
All Submodule Components Per 25 MW(e) Module	4,449 LT	7,017 LT	16,797 ft^2	361,506 ft^3	$16,855K	
Module Components						
NH$_3$ Vapor Piping	36.8 LT	37 LT	400 ft^2	3,200 ft^3	$ 75K	1
NH$_3$ Liquid Piping	25.8 LT	26 LT	300 ft^2	1,800 ft^3	$ –	1
NH$_3$ Miscellaneous	6.0 LT	6 LT	–	–	–	1
NH$_3$ Compressor	8.9 LT	9 LT	99 ft^2	396 ft^3	$ 40K	1
NH$_3$ Storage Tanks	257.1 LT	643.2 LT	5,600 ft^2	56,000 ft^3	$ 660K	16
Module Components Totals	334.6 LT	721 LT	6,399 ft^2	61,396 ft^3	$ 775K	
All Components Per 25 MW(e) Module	4,784 LT	7,738 LT	23,196 ft^2	422,902 ft^3	$17,630K	
Same in SI Units	4.77 x 10^{7}N	7.71 x 10^{7}N	2,155 m^2	11,977 m^3	$17,630K	
Per Unit Deck Area	0.206 LT/ft^2	0.334 LT/ft^2	–	–	$760/ft^2	
Per Unit Volume	0.0133 LT/ft^3	0.0183 LT/ft^3	–	–	$41.7/ft^3	
Same in lb/ft^3	29.8 lb/ft^3	41 lb/ft^3	–	–	$41.7/ft^3	
Per MW(e)	111 LT/MW	310 LT/MW	978 ft^2/MW	16,916 ft^3/MW	$705K/MW	
Packaged Module (L=157; W=60; H=118) ft	4,784 LT	7,738 LT	8,120 ft^2	1,169,280 ft^3	$17,630K	
Total/Packaged Module Per MW(e) (for 25 MW(e) Module)	111 LT/MW	310 LT/MW	325 ft^2/MW	46,771 ft^3/MW	$705K/MW	
Per Unit Volume	0.0039 LT/ft^3	0.0063 LT/ft^3	–	–	$15.0/ft^3	
Same in lb/ft^3	8.75 lb/ft^3	14.1 lb/ft^3	–	–	$15.0/ft^3	
Packing Factor = $\dfrac{PKGE}{COMPS}$	–	–	35%	276%	–	

Table 2-10
CHARACTERISTICS OF POWER SYSTEM MODULE – 12.5-MW(e) NET INTERNALLY MOUNTED CONVENTIONAL HORIZONTAL SHELL/TUBE HEAT EXCHANGERS

Components	Dry Wt.	Wet Wt.	Deck Area	Volume	Cost	No. Units/ Module
Submodule Components						
HXs	2,063 LT	3,386 LT	4,854 ft^2	145,620 ft^3	$ 4,461K	2
TG	123 LT	123 LT	768 ft^2	9,216 ft^3	1,850K	1
NH$_3$ Vapor Assembly	122 LT	122 LT	2,064 ft^2	33,024 ft^3	1,800K	3
NH$_3$ Condensate Pumps	21 LT	21 LT	176 ft^2	1,141 ft^3	565K	2
Submodule Totals	2,302 LT	3,652 LT	7,862 ft^2	189,00 ft^3	$ 8,678K	
All Submodule Components Per 25-MW(e) Module	4,602 LT	7,304 LT	15,724 ft^2	378,002 ft^3	$17,355K	
Module Components						
NH$_3$ Vapor Piping	36 LT	36 LT	480 ft^2	4,608 ft^3	$ 80K	1
NH$_3$ Liquid Piping	24 LT	24 LT	385 ft^2	2,965 ft^3		1
NH$_3$ Miscellaneous	6 LT	6 LT	–	–	–	1
NH$_3$ Compressor	9 LT	9 LT	99 ft^2	396 ft^3	$ 40K	1
NH$_3$ Storage Tanks	257 LT	643 LT	5,600 ft^2	56,000 ft^3	$ 660K	16
Module Components Totals	332 LT	718 LT	6,564 ft^2	63,969 ft^3	$ 780K	
All Components						
Per 25 MW(e) Module	4,934 LT	8,022 LT	22,288 ft^2	441,97 ft^3	$18,135K	
Same in SI Units	4.92 x 10^7 N	7.99 x 10^7 N	2,070 m^2	12,517 m^3	$18,135K	
Per Unit Deck Area	0.221 LT/ft^2	0.360 LT/ft^2	–	–	$814/ft^2	
Per Unit Volume	0.112 LT/ft^3	0.182 LT/ft^3	–	–	$41/ft^3	
Same in lb/ft^3	25.1 lb/ft^3	40.8 lb/ft^3	–	–	$41/ft^3	
Per MW(e)	197 LT/MW	321 LT/MW	892 ft^2/MW	17,679 ft^3/MW	$725K/MW	
Packaged Module (L=157; W=60; H=118) ft	4,934 LT	8,022 LT	11,826 ft^2	1,135,296 ft^3	$18,135K	
Total/Packaged Module Per MW(e) (for 25 MW(e) Module)	197 LT/MW	321 LT/MW	473 ft^3/MW	45,412 ft^3/MW	$725K/MW	
Per Unit Volume	0.0041 LT/ft^3	0.0067 LT/ft^3	–	–	$15.2/ft^3	
Same in lb/ft^3	9.18 lb/ft^3	15.0 lb/ft^3	–	–	$15.2/ft^3	
Packing Factor = $\dfrac{PKGE}{COMPS}$	–	–	45.8%	256%	–	

Table 2-11

CHARACTERISTICS OF POWER SYSTEM MODULE — 25-MW(e) NET INTERNALLY MOUNTED CONVENTIONAL HORIZONTAL SHELL/TUBE HEAT EXCHANGERS

Components	Dry Wt.	Wet Wt.	Deck Area	Volume	Cost	No. Units/ Module
Submodule Components						
HXs	4,062 LT	6,742 LT	7,690 ft^2	289,944 ft^3	$ 8,675K	2
TG	202 LT	202 LT	1,104 ft^2	13,248 ft^3	3,200K	1
NH$_3$ Vapor Assembly	203 LT	203 LT	3,440 ft^2	55,040 ft^3	3,000K	5
NH$_3$ Condensate Pumps	25 LT	25 LT	182 ft^2	1,274 ft^3	350K	2
Submodule Totals	4,492 LT	7,172 LT	12,416 ft^2	395,506 ft^3	$15,225K	
All Submodule Components Per 25 MW(e) Module	4,492 LT	7,172 LT	12,416 ft^2	395,506 ft^3	$15,225K	
Module Components						
NH$_3$ Vapor Piping	37 LT	37 LT	660 ft^2	7,260 ft^3	$ 58K	1
NH$_3$ Liquid Piping	21 LT	21 LT	540 ft^2	4,860 ft^3	$ —	1
NH$_3$ Miscellaneous	4 LT	4 LT	—	—	—	1
NH$_3$ Compressor	9 LT	9 LT	99 ft^2	396 ft^3	$ 40K	1
NH$_3$ Storage Tanks	257 LT	643 LT	5,600 ft^2	56,000 ft^3	$ 660K	16
Module Components Totals	328 LT	714 LT	6,899 ft^2	68,516 ft^3	$ 758K	
All Components Per 25 MW(e) Module	4,820 LT	7,886 LT	19,315 ft^2	464,022 ft^3	$15,983K	
Same in SI Units	4.85 x 10^{7}N	7.86 x 10^{7}N	1,794 m^3	13,141 m^3	$15,983K	
Per Unit Deck Area	0.250 LT/ft^2	0.408 LT/ft^2	—	—	$827/ft^2	
Per Unit Volume	0.0103 LT/ft^3	0.0170 LT/ft^3	—	—	$34.4/ft^3	
Same in lb/ft^3	23.1 lb/ft^3	38.1 lb/ft^3	—	—	—	
Per MW(e)	193 LT/MW	315 LT/MW	773 ft^2/MW	18,561 ft^3/MW	$639K/MW	
Packaged Module (L=157; W=60; H=118) ft	4,820 LT	7,886 LT	7,956 ft^2	922,896 ft^3	$15,983K	
Total/Packaged Module Per MW(e) (for 25 MW(e) Module)	193 LT/MW	315 LT/MW	318 LT/MW	36,916 ft^3	$639K/MW	
Per Unit Volume	0.0049 LT/ft^3	0.0081 LT/ft^3	—	—	$16.4/ft^3	
Same in lb/ft^3	11 lb/ft^3	18.1 lb/ft^3	—	—	$16.4/ft^3	
Packing Factor = $\dfrac{PKGE}{COMPS}$	—	—	41.2%	199%	—	

In order to correctly interpret these tables, it is desirable to clarify definitions of several key elements. These are as follows:

- **Sub-Module Components** — These are the Power System components which vary in size, weight, and/or cost with the size of the heat exchanger.
- **Module Components** — These are the components which are fixed for a 25-MW(e) Power System and independent of the heat exchanger employed.
- **Packaged Module** — This is the envelope generated through "optimum" arrangement of Power System components.

The data are presented in terms of sub-module components and totals first followed by module components and the cumulative totals for a 25-MW(e) module. The data set at the bottom of the table sizes and costs the packaged module, using the dimensions called out in the brackets. It is interesting to note that sizes, weights, and costs do not vary markedly between the 5, 8, 12-1/2, and 25 MW(e) sub-module packages; but in general the 25-MW(e) package employing 25-MW(e) heat exchangers tends to be the smallest, lightest, and least costly.

2.3.1.2 Alternative Power Systems.

(a) Vertical Heat Exchangers

The data supplied in Table 2-7 for vertical heat exchangers was used to generate a set of tables similar to 2-8 to 2-11 inclusive. Again, although the 25-MW(e) heat exchanger module is lightest and smallest, the improvement over the 5, 8, and 12-1/2 MW(e) heat exchanger modules is not dramatic. (See Tables 2-12 to 2-15 inclusive). In comparing these tables with those for the horizontal heat exchanges, it is apparent that the latter are larger and heavier than the vertical.

(b) Detachable Modules

Up to this point the heat exchangers under discussion have been internal to the platform. Certain configurations, particularly the Spar, are most cost-effective when coupled with detachable module Power Systems having external heat exchangers.

A summary of the analysis performed in support of detachable modules is presented below.

(a) 500 MW(e) Plant Configuration

Two types of external power modules are presented as typical of 500-MW(e) designs resulting from the given set of components. The considerations which most strongly influence the design are:

- Reasonable seawater routing through the platform and power module, i.e., most direct path, minimum resistance, and minimum structure for seawater ducting
- Reasonable ammonia vapor routing, i.e., minimum duct length and minimum bends. Mist extractor requirements force compromises on this objective
- Structural integrity and producibility
- Towability
- Maintainability through ready access to maintained components
- Minimum recirculation of evaporator efflux back to warm water inlet

The requirements lead to an axisymmetric arrangement with ten wedge shaped power module stations positioned radially around the control platform core. Two 25-MW(e) capacity power modules, or a single dual 50-MW(e) capacity power module, are fitted into each station. This dictates a slender vertical arrangement within the power module. The baseline arrangement uses 20 each of the 25-MW(e)-size horizontal cylindrical evaporators and condensers. Alternative arrangements, using vertical cylindrical heat exchangers, or spherical heat exchangers of either orientation, are discussed briefly.

Two power modules with horizontal cylindrical 25-MW(e) heat exchangers were con-figured — one type with a single evaporator and condenser, the other a dual 50-MW(e) capacity module with one pair each of evaporators and condensers. Platform layouts suitable for each type are presented. In addition, two vertical heat exchanger modules were sketched to illustrate the effect of this arrangement on platform design.

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Table 2-12

CHARACTERISTICS OF POWER SYSTEM MODULE – 5-MW(e) NET INTERNALLY MOUNTED CONVENTIONAL VERTICAL SHELL/TUBE HEAT EXCHANGERS

Components	Dry Wt.	Wet Wt.	Deck Area	Volume	Cost	No. Units/ Module
Submodule Components						
HXs	332 LT	560 LT	986 ft^2	45,932 ft^3	$ 1,875K	2
TG	49 LT	49 LT	320 ft^2	2,560 ft^3	700K	1
NH$_3$ Vapor Assembly	41 LT	41 LT	688 ft^2	11,008 ft^3	600K	1
NH$_3$ Condensate Pumps	11 LT	11 LT	110 ft^2	550 ft^3	350K	2
Submodule Totals	433 LT	561 LT	2,104 ft^2	60,050 ft^3	$ 3,525K	
All Submodule Components Per 25 MW(e) Module	2,165 LT	3,305 LT	10,530 ft^2	300,250 ft^3	$17,625K	
Module Components						
NH$_3$ Vapor Piping	38.2 LT	38 LT	239 ft^2	1,264 ft^3	$ 67K	1
NH$_3$ Liquid Piping	26.8 LT	27 LT	144 ft^2	461 ft^3	–	1
NH$_3$ Miscellaneous	6.0 LT	6 LT	–	–	–	1
NH$_3$ Compressor	8.9 LT	9 LT	99 ft^2	395 ft^3	$ 40K	1
NH$_3$ Storage Tanks	257.1 LT	643 LT	5,600 ft^2	56,000 ft^3	$ 660K	16
Module Components Totals	337 LT	723 LT	6,082 ft^2	58,121 ft^3	$ 767K	
All Components Per 25 MW(e) Module	2,502 LT	4,028 LT	16,602 ft^2	358,371 ft^3	$18,142K	
Same in SI Units	2.49 x 10^7 N	4.01 x 10^7 N	1,542 m^2	10,144 m^3	$18,142K	
Per Unit Deck Area	0.151 LT/ft^2	0.242 LT/ft^2	–	–	$1,092/ft^2	
Per Unit Volume	0.00698 LT/ft^3	0.0112 LT/ft^3	–	–	$50.6/ft^3	
Same in lb/ft^3	15.6 lb/ft^3	25.1 lb/ft^3	–	–	$50.6/ft^3	
Per MW(e)	100 LT/MW	161 LT/MW	664 ft^2/MW	14,335 ft^3/MW	$726K/MW	

Table 2-13

CHARACTERISTICS OF POWER SYSTEM MODULE — 8-MW(e) NET INTERNALLY MOUNTED CONVENTIONAL VERTICAL SHELL/TUBE HEAT EXCHANGERS

Component	Dry Wt.	Wet Wt.	Deck Area	Volume	Cost	No. Units/ Module
Submodule Components						
HXs	538 LT	894 LT	1,352 ft^2	73,684 ft^3	$ 3,008K	2
TG	81 LT	81 LT	500 ft^2	5,000 ft^3	1,060K	1
NH_3 Vapor Assembly	81 LT	81 LT	1,376 ft^2	22,016 ft^3	1,200K	2
NH_3 Condensate Pumps	17 LT	17 LT	127 ft^2	696 ft^3	350K	2
Submodule Totals	717 LT	1,073 LT	3,355 ft^2	101,396 ft^3	$ 5,618K	
All Submodule Components Per 25 MW(e) Module	2,151 LT	3,219 LT	10,065 ft^2	304,188 ft^3	$16,855K	
Module Components						
NH_3 Vapor Piping	37 LT	37 LT	400 ft^2	3,200 ft^3	$ 75K	1
NH_3 Liquid Piping	26 LT	26 LT	300 ft^2	1,800 ft^3	–	1
NH_3 Miscellaneous	6 LT	6 LT	–	–	–	1
NH_3 Compressor	9 LT	9 LT	99 ft^2	396 ft^3	$ 40K	1
NH_3 Storage Tanks	257 LT	643 LT	5,600 ft^2	56,000 ft^3	$ 660K	16
Module Components Totals	345 LT	721 LT	6,399 ft^2	106,396 ft^3	$ 775K	
All Components Per 25 MW(e) Module	2,486 LT	3,940 LT	16,464 ft^2	410,584 ft^3	$17,630K	
Same in SI Units	2.48×10^7 N	3.93×10^7 N	1,530 m^2	38,143 m^3	$17,630K	
Per Unit Deck Area	0.151 LT/ft^2	0.239 LT/ft^2	–	–	$1,071K/ft^2$	
Per Unit Volume	0.00685 LT/ft^3	0.0096 LT/ft^3	–	–	$42.9K/ft^3$	
Same in lb/ft^3	15.3 lb/ft^3	21.5 lb/ft^3	–	–	$42.9/ft^3$	
Per MW(e)	99 LT/MW	158 LT/MW	659 ft^2/MW	16,423 ft^3/MW	$705K/MW	

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Table 2-14

CHARACTERISTICS OF POWER SYSTEM MODULE – 12.5-MW(e) NET INTERNALLY MOUNTED
CONVENTIONAL VERTICAL SHELL/TUBE HEAT EXCHANGERS

Component	Dry Wt.	Wet Wt.	Deck Area	Volume	Cost	No. Units/ Module
Submodule Components						
HXs	844 LT	1,402 LT	1,812 ft^2	114,700 ft^3	$ 4,461K	2
TG	123 LT	123 LT	768 ft^2	9,215 ft^3	1,850K	1
NH$_3$ Vapor Assembly	122 LT	122 LT	2,064 ft^2	33,024 ft^3	1,800K	3
NH$_3$ Condensate Pumps	21 LT	21 LT	176 ft^2	1,141 ft^3	565K	2
Submodule Totals	1,110 LT	1,668 LT	4,820 ft^2	158,081 ft^3	$ 8,678K	
All Submodule Components Per 25 MW(e) Module	2,220 LT	3,336 LT	9,640 ft^2	316,162 ft^3	$17,355K	
Module Components						
NH$_3$ Vapor Piping	36 LT	36 LT	480 ft^2	4,608 ft^3	$ 80K	1
NH$_3$ Liquid Piping	24 LT	24 LT	385 ft^2	2,565 ft^3	–	1
NH$_3$ Miscellaneous	6 LT	6 LT	–	–	–	1
NH$_3$ Compressor	9 LT	9 LT	99 ft^2	396 ft^3	40K	1
NH$_3$ Storage Tanks	257 LT	643 LT	5,600 ft^2	56,000 ft^3	660K	16
Module Components Totals	332 LT	718 LT	6,564 ft^2	63,969 ft^3	$ 780K	
All Components Per 25 MW(e) Module	2,554 LT	4,054 LT	14,392 ft^2	380,131 ft^3	$18,135K	
Same in SI Units	2.54 x 10^7 N	4.04 x 10^7 N	1,337 m^2	35,314 m^3	$18,135K	
Per Unit Deck Area	0.158 LT/ft^2	0.250 LT/ft^2	–	–	$1,119/ft^2	
Per Unit Volume	0.00672 LT/ft^3	0.0107 LT/ft^3	–	–	$47.7/ft^3	
Same in lb/ft^3	15.1 lb/ft^3	24.0 lb/ft^3	–	–	$47.7/ft^3	
Per MW(e)	102 LT/MW	162 LT/MW	648 ft^2/MW	15,205 ft^3/MW	$725K/MW	

Table 2-15

CHARACTERISTICS OF POWER SYSTEM MODULE – 25-MW(e) NET INTERNALLY MOUNTED
CONVENTIONAL VERTICAL SHELL/TUBE HEAT EXCHANGERS

Components	Dry Wt.	Wet Wt.	Deck Area	Volume	Cost	No. Units/ Module
Submodule Components						
HXs	1,688 LT	2,794 LT	2,872 ft^2	228,676 ft^3	$ 8,675K	2
TG	202 LT	202 LT	1,104 ft^2	13,248 ft^3	3,200K	1
NH$_3$ Vapor Assembly	203 LT	203 LT	3,440 ft^2	55,040 ft^3	3,000K	5
NH$_3$ Condensate Pumps	25 LT	25 LT	182 ft^2	1,274 ft^3	350K	2
Submodule Totals	2,918 LT	3,224 LT	7,598 ft^2	298,238 ft^3	$15,225K	
All Submodule Components Per 25 MW(e) Module	2,918 LT	3,224 LT	7,598 ft^2	298,238 ft^3	$15,225K	
Module Components						
NH$_3$ Vapor Piping	37 LT	37 LT	660 ft^2	7,260 ft^3	$ 58K	1
NH$_3$ Liquid Piping	21 LT	21 LT	540 ft^2	4,860 ft^3	–	1
NH$_3$ Miscellaneous	4 LT	4 LT	–	–	–	1
NH$_3$ Compressor	9 LT	9 LT	99 ft^2	396 ft^3	$ 40K	1
NH$_3$ Storage Tanks	257 LT	643 LT	5,600 ft^2	56,000 ft^3	$ 660K	16
Module Components Totals	328 LT	714 LT	6,899 ft^2	68,516 ft^3	$ 758K	
All Components Per 25 MW(e) Module	3,246 LT	3,938 LT	14,497 ft^2	366,754 ft^3	$15,983K	
Same in SI Units	3.23 x 10^{7}N	3.92 x 10^{7}N	1,347 m^2	34,071 m^3	$15,983K	
Per Unit Deck Area	0.224 LT/ft^2	0.272 LT/ft^2	–	–	$1,103/ft^2	
Per Unit Volume	0.00885 LT/ft^3	0.0107 LT/ft^3	–	–	$43.6/ft^3	
Same in lb/ft^3	19.8 lb/ft^3	24.0 lb/ft^3	–	–	$43.6/ft^3	
Per MW(e)	130 LT/MW	178 LT/MW	580 ft^2/MW	14,670 ft^3/MW	$639K/MW	

(1) 25-MW(e) Power Module

This arrangement has the required slender configuration and provides the most compact and direct routing of ammonia vapor. However, it requires interlacing of seawater delivery paths since the locations of evaporator and condenser are inverted relative to the thermal gradient, as shown in Fig. 2-9.

25 MW(e) POWER
SYSTEM MODULE.
20 EACH ATTACHED AROUND
CORE IN TWO LEVELS OF 10
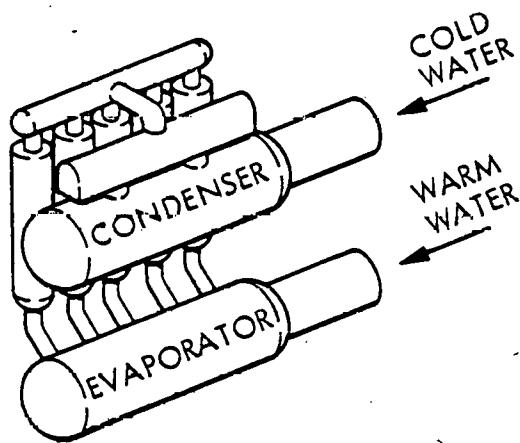
a. Component layout
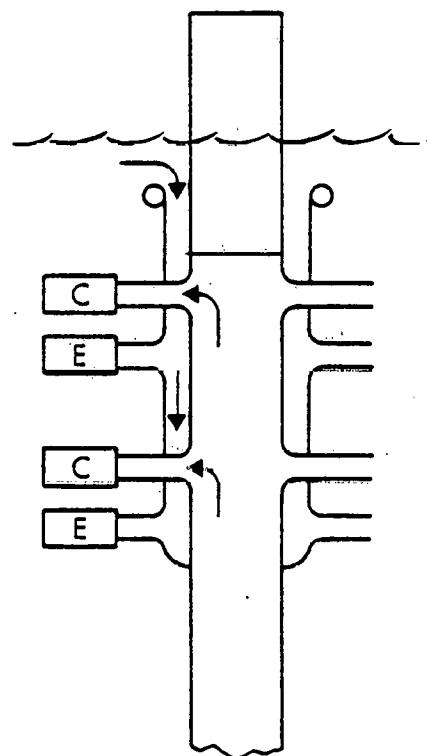
b. Spar buoy platform arrangement and seawater flow routing

Fig. 2-9 25-MW(e) Power Module Application

The seawater routing requirement is accommodated by the arrangement shown on the right. The advantages (+) and disadvantages (-) of this arrangement are:

- Requires more platform structure than equivalent non-inverted power module (-).
- Has higher seawater flow losses (-)
- Is adaptable to any arrangement of heat exchangers (+)
- May reduce recirculation through interactions of heat exchanger effluxes in inverted locations (+)

No structural interconnections, buoyancy requirements, or deployment considerations have been worked out for this power module. However, no difficulties in these areas are foreseen.

(2) 50-MW(e), Dual-25 Power Module Application

The 50-MW(e) dual-25 power module is shown in Fig. 2-10. The considerations leading to this arrangement are:

- Slender profile to allow close packing around control core
- Most direct seawater routing
- Acceptable configuration for towing
- Turbogenerators and pumps contained within pressure hulls for manned access
- Feasibility of direct structural interconnection of components
- Directness of ammonia flow paths compromised in favor of other objectives

A suggested structural concept is shown in Fig. 2-11. The cylindrical modules can be fabricated in a relatively shallow protected site and floated to deeper water for assembly. Assembly is done sequentially with all work taking place at or near the surface, the spar buoy being gradually submerged as the vertical stacking of modules proceeds.

This arrangement is adaptable to a variety of power module layouts. It provides space in the central core or in a "top-hat" above the waterline for manned and process equipment spaces. Alternatively, the spar can be completely passive, containing only buoyancy spares, seawater ducting, and mooring.

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LEGEND

C = CONDENSER, 25 MW(e)
D = DEMISTER, 5 MW(e)
E = EVAPORATOR, 25 MW(e)
T = TURBOGENERATOR, 25 MW(e)
P = PUMP HOUSING
SWP = SEAWATER PUMP

THIN PLATE FAIRWATER TANGENT TO
SEAWATER PUMP AND HEAT EXCHANGER
SHELLS

PRESSURE VESSEL
CONTAINS TURBO-
GENERATORS IN
SHIRT-SLEEVE
ENVIRONMENT

COMPARTMENTS
BETWEEN SEAWATER
PUMPS AND HEAT
EXCHANGERS
FLOODED OR VOID
AS NECESSARY FOR
TRIM DURING TOWING
AND SUBMERGENCE

POWER MODULE FLOATING
HORIZONTALLY FOR TOWING

312 FT
T

58 FT

170 FT

0 20 40 100
10 30 50
SCALE, FT

MAIN LONGITUDINAL STRUCTURAL
INTERCONNECTIONS MADE IN
PLANE OF HEAT EXCHANGER TUBE-
SHEETS AND SEAWATER PUMP MOUNTING
FLANGES
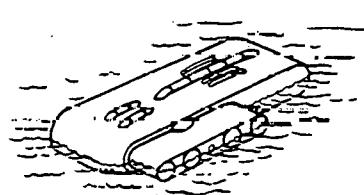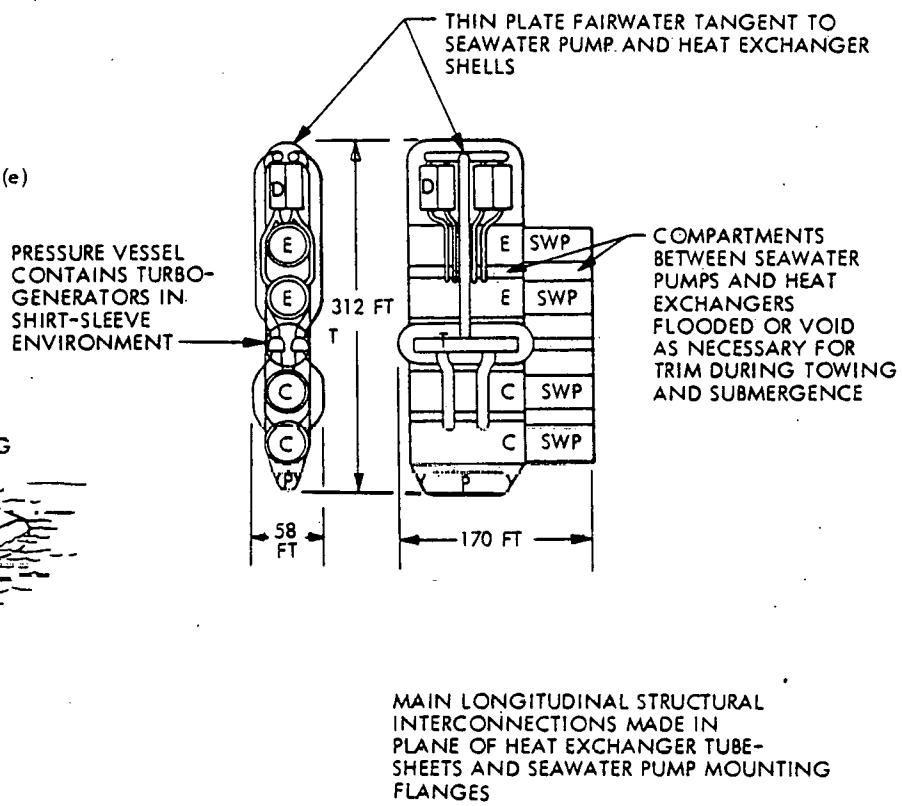
Fig. 2-10 50-MW(e) Net External Power System Module.
Units are 25-MW(e) net horizontal

(3) Vertical Heat Exchanger Power Modules

Layouts were prepared for 50 MW(e) dual-25 power modules with vertical heat exchangers.
Figure 2-12 shows the cylindrical type as described in Table 2-7.

● Places equipment at a greater depth, particularly cold seawater pumps (-)

● Heat exchanger inlets and outlets in most advantageous orientation to avoid
  recirculation (+)

● Component arrangement lends itself to power module structural integrity and
  a good towing configuration (+)

● The platform contains no warm seawater ducting so may be reduced to the
  ultimate simplicity – a cold water pipe and buoyancy tank (+)

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10 LOCATIONS FOR POWER MODULES AROUND PERIPHERY OF SPAR

HEAT EXCHANGER

A

SEAWATER PUMP

VERTICAL STACKING OF MODULES

HEAT EXCHANGER

SEAWATER PUMP

CORE

BUOYANCY TANK

SPACE FOR SEAWATER GATE VALVE

COFFERDAM FOR BUOYANCY DURING TRANSIT. REMOVE AFTER ASSEMBLY
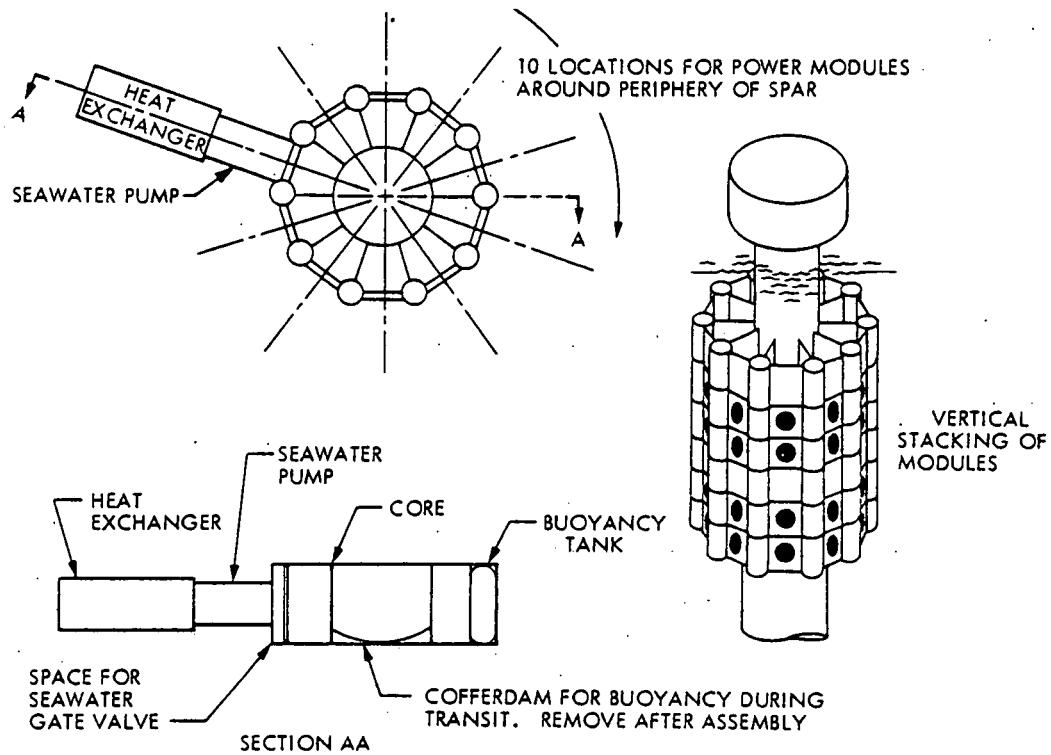
SECTION AA

Fig. 2-11 500-MW(e) Spar With External Power Modules —
Modular Construction

LEGEND

C = CONDENSER, 25 MW$_{(e)}$
D = DEMISTER, 5 MW$_{(e)}$
E = EVAPORATOR, 25 MW$_{(e)}$
T = TURBOGENERATOR, 25 MW$_{(e)}$
SWP = SEAWATER PUMP, 25 MW$_{(e)}$

AMMONIA PUMPS AND
STORAGE NOT SHOWN

INTERCONNECTING STRUCTURE
NOT SHOWN. SPACE-FRAME
STRONGBACK ALONG CENTER-
LINE BETWEEN HEAT EXCHANGERS
IS SUGGESTED

T

E   E

60 FT

D

SWP

D D D

E

D D D   D D D

E   E

390 FT

C

SWP

C   C

SWP SWP

114 FT

0 20 40   100
10 30 50
SCALE, FT.
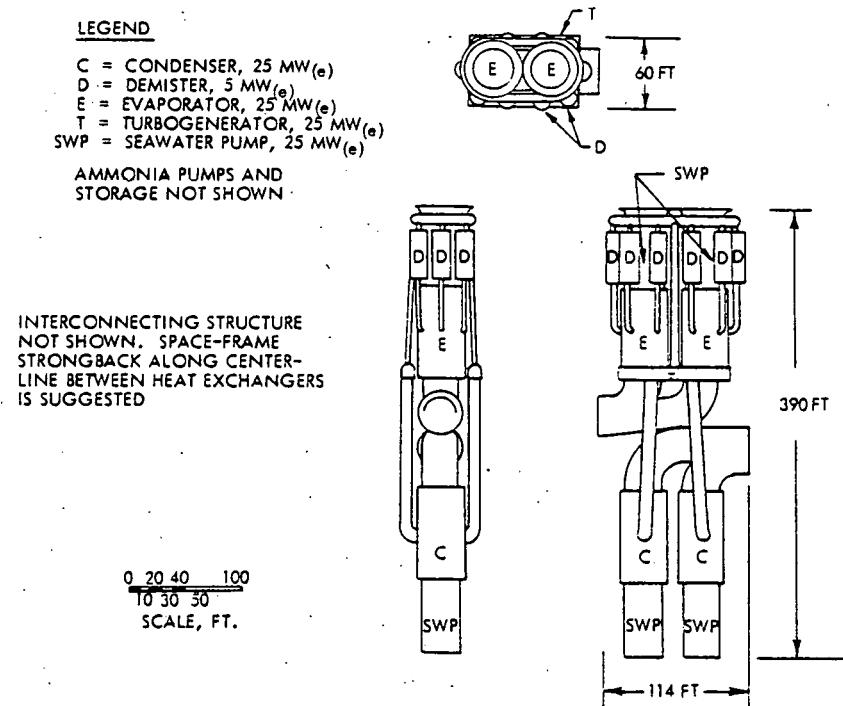
Fig. 2-12 50-MW(e) Net External Power System Module.
Units are 25-MW(e) (net) vertical

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(b) 100 MW(e) Plant Configuration

The design concepts described in the previous sections have been applied to layout of 25-MW(e) power modules, of which four are attached to a central core to form a 100-MW(e) plant. The arrangements shown may have horizontal cylindrical, vertical cylindrical, or vertical spherical heat exchanges. The horizontal cylindrical and spherical vertical power modules (Fig. 2-13) are shown with monocoque shell interconnecting structure, while a space-frame structure is suggested for the vertical cylindrical module (Fig. 2-14). In general, the comments on the power module configurations for the 500-MW(e) plant apply to the similar designs presesented here.

HORIZONTAL CYLINDRICAL HEAT EXCHANGERS
BASED ON GOVERNMENT FURNISHED DATA
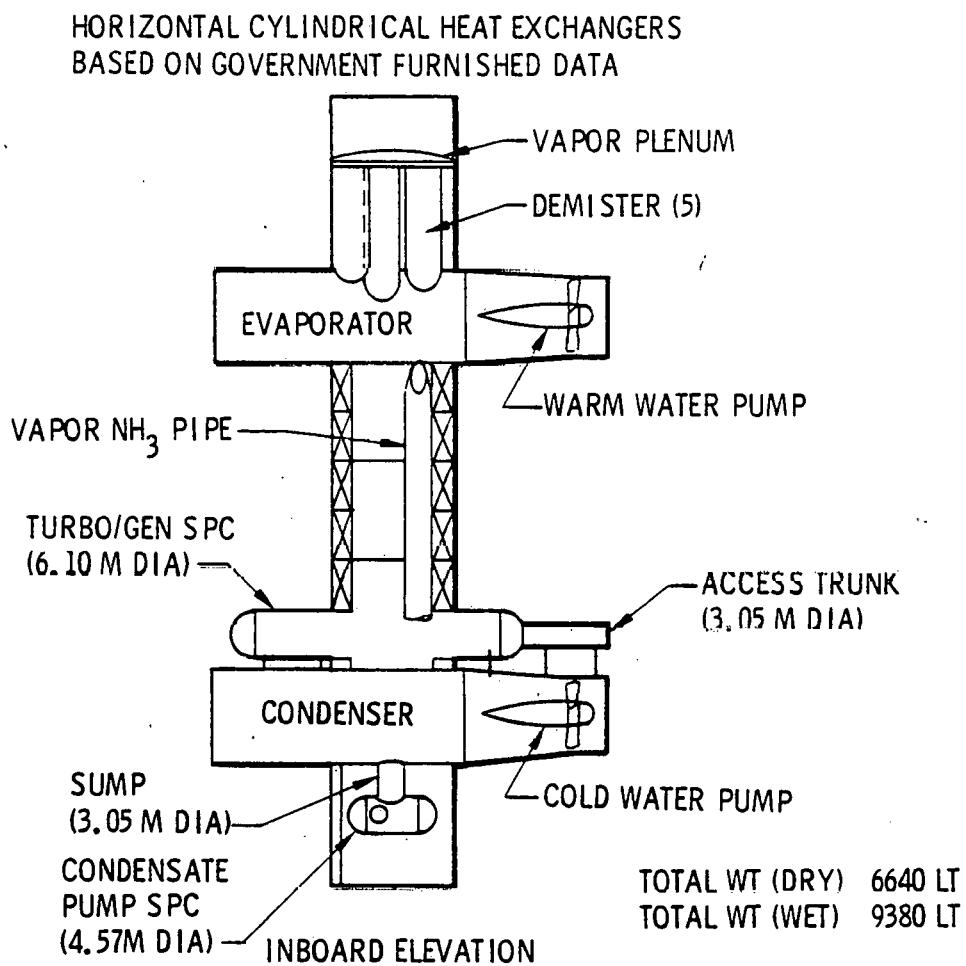
Fig. 2-13 25-MW(e) Detachable Power Module

2-36

LEGEND

C = CONDENSER, 25 MW$_{(e)}$
D = DEMISTER, 5 MW$_{(e)}$
E = EVAPORATOR, 25 MW$_{(e)}$
T = TURBOGENERATOR, 12.5 MW$_{(e)}$
SWP = SEAWATER PUMP, 25 MW$_{(e)}$

AMMONIA PUMPS AND
STORAGE NOT SHOWN

SCALE, FT

INTERCONNECTING STRUCTURE
NOT SHOWN. SPACE FRAME
WITH FOUR EQUALLY SPACED
MAIN VERTICAL MEMBERS IS
SUGGESTED.
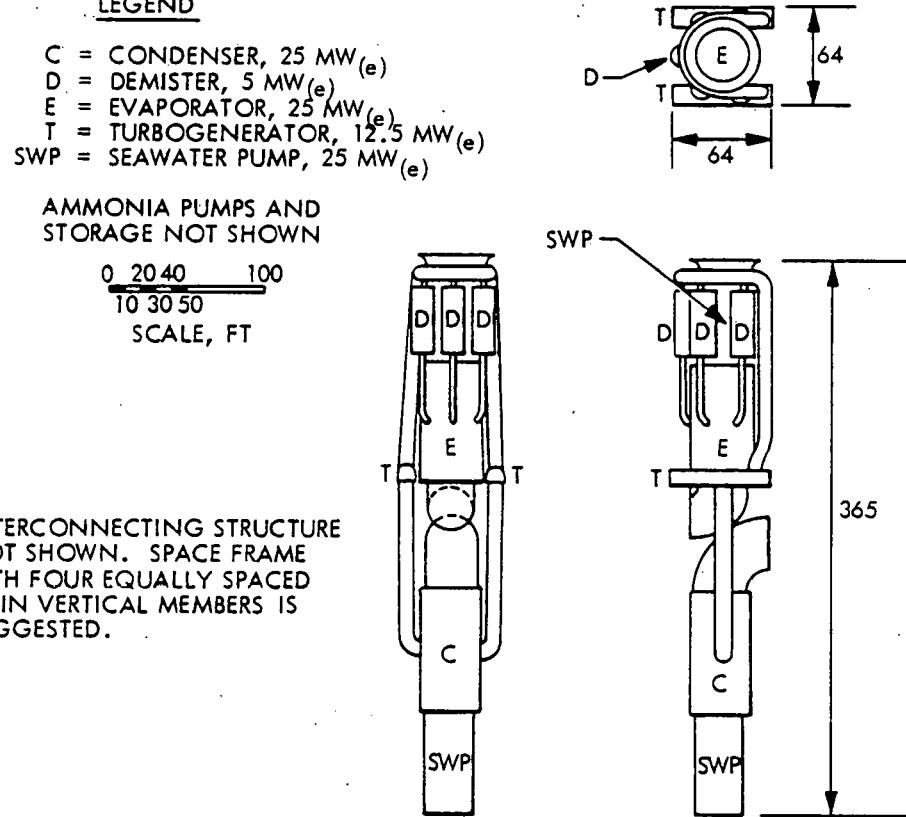
Fig. 2-14 25-MW(e) Net External Power System Module

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References

1. Letter, Mr. D. Price (GTR) to Mr. R. Waid (LMSC Proj. Mgr.) "Transmittal of OTEC Power Requirements as Generated by Gilbert Associates," File No. EG-77-C-01-4063, 16 Aug 1977.

2. Memorandum, Mr. R. Berg (Gilbert Assoc.) to Mr. D. Price (GTR) "Transmittal of Heat Exchanger Design Information", 23 August 1977

2.3.2 Energy Transfer System

Consideration of the Energy Transfer System provides criteria for selection of the preferred configurations and plant size (generating capacity). These are:

- Minimum cost, evaluated for the case of an OTEC park of 3000 MW(e) total capacity
- Adequate space for chemical conversion equipment

The approach for electrical transmission is to postulate various arrangements of plants throughout the park resource area, and various plant sizes, determining the cost in each case. The observable trends then give guidance to the selection process. The requirements imposed by chemical conversion equipment are considered separately.

The arrangements considered are three:

- Plants uniformly distributed throughout an approximately circular resource area
- Plants clustered throughout the approximately circular resources area
- Plants in a line across a unidirectional current

Plant sizes considered range from 50 to 500 MW(e). Net powers actually assumed for computation purposes were 50, 80, 160, and 500 MW(e).

System cost is calculated for each arrangement and plant size. For the distributed and clustered arrangement, this also involves optimizing the plant spacing. The cost does not include the step-up transformer or AC-DC conversion equipment which prepares the power for transmission to shore, nor does it include the shore cable cost, these items being the same for all examples. The method is discussed and the results summarized below.

2.3.2.1 Spacing Optimization Analysis. At a particular site location, given the size of each plant and the total capacity of all the plants to be emplaced, plant spacing is determined by a tradeoff between two factors:

- Plant cost – larger spacing results in less reduction of seawater surface temperature due to withdrawal of thermal energy, maintaining a larger temperature differential and more efficient power cycle operation, thereby reducing plant cost of fixed power output
- Cable cost – smaller spacing results in shorter cables, thereby reducing the cost of the electrical power collection network connecting the array of plants

The optimization procedure is to minimize total system cost as a function of plant spacing, expressed in terms of the ocean area throughout which the plants are distributed.

Plant Cost as a Function of Spacing. Determination of plant cost as a function of spacing is a three-step process:

(1) Formulation of a model describing the processes of energy withdrawal from the warm sea surface layer
(2) Determination of the depression of sea surface layer temperature as a function of the rate of energy withdrawal
(3) Evaluation of the increase in plant cost as a function of the depression of sea surface layer temperature

This analysis assumes that the cold water resource is not affected by the operation of the plants.

The energy withdrawal model represents the OTEC plant as a sink for warm ocean surface water. This sink imposes a load on the existing thermal resource. Analysis of the load includes determination of the depth and horizontal extent of the sea volume from which water is drawn, the amount of recirculation of seawater from heat exchanger outlets back to inlets, and the mixing of cooler subsurface waters into the surface layer, all as a function of plant size, local ocean currents, and temperature profiles.

In this section we have assumed that recirculation in the neighborhood of the plant is negligible, and that the plant draws warm water uniformly from a region of radius (or half-width in the case of ocean currents) equal to half the plant spacing. The evaporator seawater discharge is below the mixed layer and flows outward to "infinity" without short-circuiting into the inward flow.

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This assumption is based on the presence of the thermocline which strongly inhibits vertical transport phenomena. However, the thermocline is not a perfect barrier, so the plant-induced flow field will actually decay with distance away from the plant. Additional analysis is required to determine whether this decay distance is large when compared to the plant spacings, as assumed here.

Further, we have assumed that the entire evaporator heat flow is withdrawn from the surface layer and deposited below the mixed layer. Therefore, for an OTEC park of P_e total capacity, made up of plants operating at η_t thermal-to-electrical conversion efficiency, the total thermal load is P_e/η_t.

In the case where the OTEC park consists of plants distributed uniformly throughout resource area A_r, the thermal flux ϕ_t drawn out of the warm surface layer is, on the average

$$\phi_t = \frac{P_e}{\eta_t A_r} \qquad \text{(Eq. 1)}$$

The effect of withdrawing this thermal flux ϕ_t is to perturb the thermal equilibrium of the warm surface layer, causing its temperature T_s to drop to a lower value. The magnitude of the temperature drop is calculated by methods described by Fry (Ref. 1) and Blathen (Ref. 2). The calculation determines the heat balance of a control volume consisting of a unit area of the mixed layer. Heat transfer across the boundaries of the control volume occurs by:

- Radiation at the water-air interface
- Evaporation at the water-air interface
- Conduction/convection at the air-water interface
- Advection (currents) laterally within the mixed layer

The heat flux is calculated as a function of surface temperature T_s for each of the heat transfer mechanisms listed; and then the terms are summed to give the total flux ϕ. The unperturbed surface temperature is the one for which ϕ equals zero.

The effect of the OTEC park is determined by first calculating $d\phi/dT_S$, then computing

$$\Delta T_S = \frac{\phi_t}{d\phi/dT_S} \qquad \text{(Eq. 2)}$$

The references give values of $d\phi/dT_S$, as tabulated in Table 2-16 for particular sites, assuming that the plants are distributed uniformly throughout the resource area.

Table 2-16

VALUES OF $d\phi/dT_S$ FOR PARTICULAR SITES

Site	Reference	$d\phi/dT_S$
Caribbean Ocean, Excluding Current Contribution	(1)	-18.7 $MW_t/mi^2 \cdot F$ -13.7 $MW_t/Km^2 \cdot C$
Caribbean Ocean, Including Currents	(1)	-48 $MW_t/mi^2 \cdot F$ -35.2 $MW_t/Km^2 \cdot C$
Keahole Point, Hawaii	(2)	-39 $MW_t/mi^2 \cdot F$ -28.7 $MW_t/Km^2 \cdot C$

The effect of the depression of T_S by OTEC park operation is to increase the cost of the plant required to generate a given net output. For small perturbations in T_S, the cost relationship is linear,

$$C_p = C_{po} (1 - K_c \Delta T_S) \qquad \text{(Eq. 3)}$$

where C_p is plant cost, C_{po} is plant cost at zero ΔT_S, and K_c is the cost-temperature coefficient. It can be shown that K_c has the same value as the slope of the curves of plant output vs. temperature, such as those shown in Fig. 2-15, based on computer calculated performance.
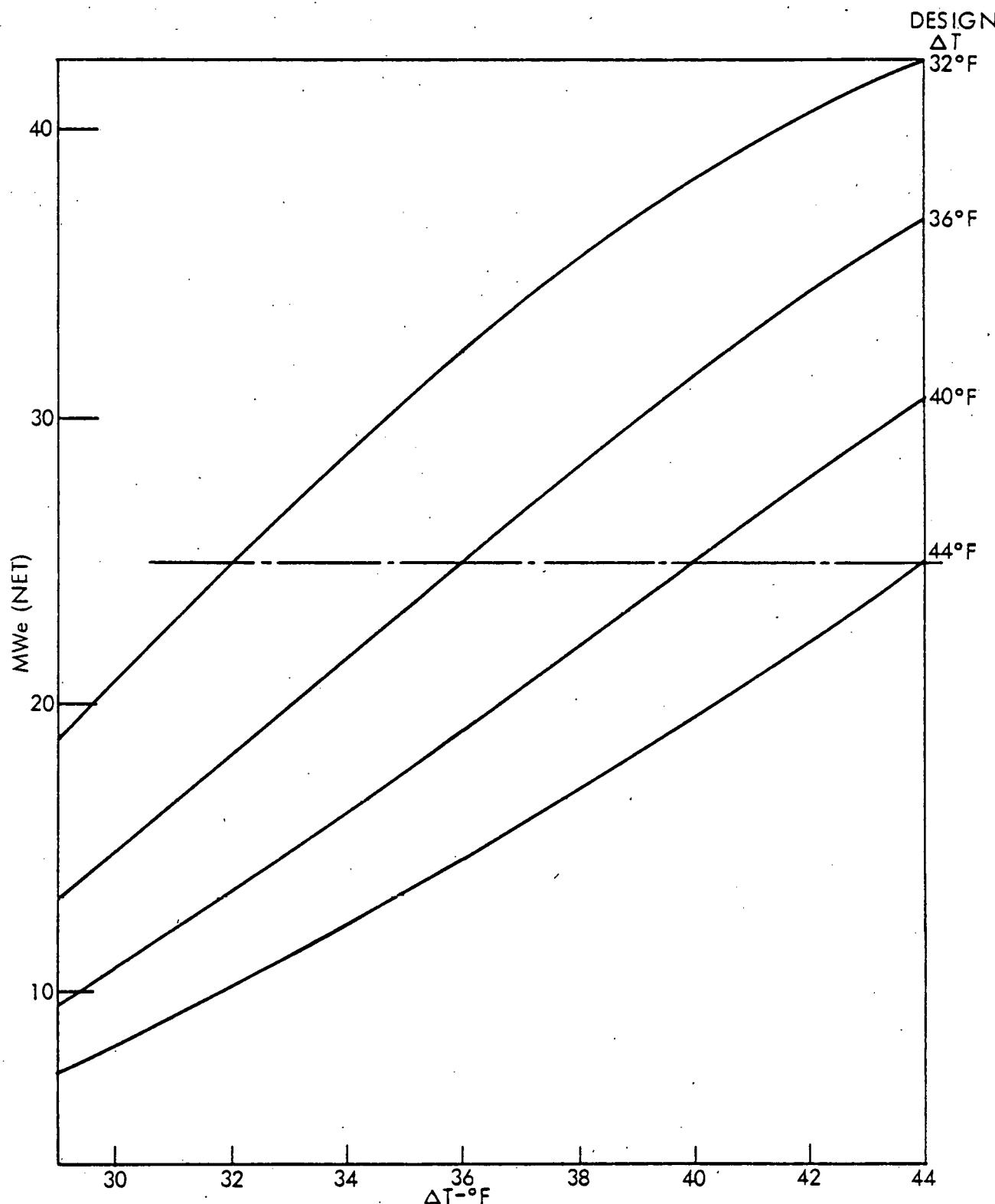
Fig. 2-15 Off-Design Performance of 25-MW(e) (Net) Module

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From an average of these data we determine the value

$$K_c = 0.0668 \ (^\circ F)^{-1} \quad \text{or} \quad 0.127 \ (^\circ C)^{-1} \qquad \text{(Eq. 4)}$$

We can now express the change in plant cost as a function of the parameters defined above.

$$\Delta C_p = - \frac{K_o \ P_o \ C_{po}}{\eta_t A_r \ d\phi/dT_s} \qquad \text{(Eq. 5)}$$

This relationship is valid for plants distributed uniformly throughout a resource area A_r and drawing warm water uniformly from the whole area.

When a steady, unidirectional current exists, it may be advantageous to arrange the OTEC park plants in a line perpendicular to the current flow. In this case, the plant spacing necessary for safety, i.e., collision avoidance in rough weather, is usually much greater than the width of the stream tube which is drawn into the evaporators. As a result, the plants do not interact in their effect on the resource (provided that plants are not placed such that their wakes impinge on others downstream).

However, the size of the plant determines its effect on the resource. A larger plant, with greater seawater flow, draws its warm water inflow from a greater depth. As a result, the average inflow temperature $\overline{T}_s$ is lower. This effect is evaluated by Fry (Ref. 1) for Caribbean Ocean conditions. In general, the depression $\Delta \overline{T}_s$ of average surface temperature is a function of plant net power P_p, efficiency η_t, and site dependent variables

$$\Delta \overline{T}_s = \text{fn} \ (P_p/\eta_t, \ \text{site dependent variables}) \qquad \text{(Eq. 6)}$$

The resultant change in plant cost is, as before

$$\Delta C_p = C_{po} \ K_c \ \Delta \overline{T}_s \qquad \text{(Eq. 7)}$$

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This relation is valid for a line of OTEC plants arrayed perpendicularly across a unidirectional current.

Cable Cost as a Function of Spacing. The cost C_c of the interconnecting cables is simply the product of the average cable length $\overline{L}_c$, the number of cables per plant N_c, the number of plants in the park N_p, and the installed cable cost per unit length F_c,

$$C_c = \overline{L}_c \, N_c \, N_p \, F_c \qquad \text{(Eq. 8)}$$

The average cable length will be expressed as the product of average plant spacing S and a constant K_s, which account for the site factors which prevent cables from being laid along the most direct paths, and variations in plant locations from a geometrically uniform grid. For this study we assume $K_s = 1.2$.

Plant spacing is determined by assuming that each plant occupies a hexagonal area of dimension S between opposite sides, having six equidistant nearest neighbors. The resource area A_r occupied by N_p plants is, therefore

$$A_r = N_p \, S^2 \frac{\sqrt{3}}{2} \qquad \text{(Eq. 10)}$$

Solving for spacing S,

$$S = \sqrt{\frac{2 A_r}{\sqrt{3} \, N_p}} = 1.075 \sqrt{\frac{A_r}{N_p}} \qquad \text{(Eq. 11)}$$

and the cable cost is

$$C_c = 1.075 \, K_s \sqrt{A_r \, N_p} \, N_c \, F_c \qquad \text{(Eq. 12)}$$

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Riser and Cable Junction Costs. Cable risers and junctions are necessary to complete the power collection network.

The riser is a special cable, designed to withstand the varying tension and bending loads, and the abuse of being dragged across the bottom, resulting from plant motions. Its cost per unit length F_r is therefore two to five times the material cost of the bottom cables. For purposes of this study, we assume the riser takes a catenary form from plant to bottom approximated by a quarter circle. The riser length L_r, in terms of ocean depth D, is

$$L_r = \frac{\pi}{2} D \qquad \text{(Eq. 13)}$$

and the cost of the riser, C_r, is

$$C_r = F_r L_L = \frac{\pi}{2} F_r D \qquad \text{(Eq. 14)}$$

A cable junction is required at every node in the power collection network where power from two or more plants is merged. The equipment types which might be included in the junction are

- Cable terminal – the mechanical and electrical connection of a single cable into the power circuit. Cable replacement takes place by physically disconnecting the cable at the terminal
- Disconnect switch – makes or breaks the circuit between a cable terminal and the rest of the circuit. Can be operated only when the circuit is not energized
- Circuit breaker – capable of interrupting the circuit while energized, particularly for fault isolation
- Line compensation – discrete reactive elements placed across an AC transmission line to compensate for the cable capacitance
- Power converters – used here to include both transformers for changing the voltage of AC circuits, and AC-DC converters

The simplest junction would contain only cable terminals. This would require shutting down the entire system for the duration of the maintenance period should cable repair or replacement be required.

The next simplest junction would include disconnect switches. This would require the system to shut down only for the moment required to actuate the switches which isolate the cable requiring work.

It is conceivable that junctions containing either of these equipment types could be placed on the sea bottom and be operated remotely for an extended period. The more complex equipment is, however, not adequately qualified at present for such service, although it is technically feasible to qualify this equipment for such service if the need is demonstrated.

The resulting tradeoff is between use of subsurface junctions which do not require risers for their connecting cables but require the entire park to shut down if repairs are needed, versus surface junctions which do require additional risers but can instantly isolate a section of cable requiring attention without interrupting operation of the rest of the park. In this report, the surface junction alternative is chosen.

The cost of a junction component is proportional to its power rating. Thus the cost of all the junctions in the system is proportional to the cumulative sum of all the power handled by the system, i.e., the contribution of a single plant to the cumulative power sum is the capacity of that plant times the number of junctions through which the plant's power passes. With specific cost F_j per unit of capacity, and cumulative power P_j, the cost C_j of junction equipment is

$$C_j = F_j P_j \qquad \text{(Eq. 15)}$$

This report assumes that all junctions are housed aboard plant platforms. This ignores the one exception, which is the park consisting of a few plants, or clusters of plants, which has a central power collection junction site where no plant is located. The

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justification for ignoring this cost element is (1) it is a small contribution to the total cost of the park, (2) it is independent of plant size or spacing, and (3) generating an accurate estimate of its cost requires effort exceeding its present usefulness.

In summary, the cost of risers and junctions is

$$N_r C_r + C_j = \frac{\pi}{2} N_r F_r D + F_j P_j \qquad \text{(Eq. 16)}$$

where N_r is the number of risers in the system. N_r depends on system layout, so rather than presenting a general expression in terms of the number of plants and a layout-dependent parameter, it is expedient to simply count the risers for the specific cases considered.

OTEC Park Cost. Combining all the cost terms, the total OTEC park cost is

$$C = C_{po} \left(1 - \frac{K_c P_e}{\eta_t A_r \, d\phi/dT_s} \right) + 1.075 \, K_s \, \sqrt{A_r N_p} \, N_c F_c + \frac{\pi}{2} N_r F_r D + F_j P_j$$

$$\text{(Eq. 17)}$$

for a park with plants distributed throughout an area A_r. For the linear cross-current arrangement, the cost is computed employing a modified relation. The plant cost term is computed using $\overline{T}_s$ based on ingestion of warm water from the current flowing around the plant. The length of cable between each plant is the plant spacing, subtracting the horizontal extension of the risers from plant to cable. Assuming the junctions are made on the plants, cable length L_c is

$$L_c = S - 2D \qquad \text{(Eq. 18)}$$

The riser and junction costs are calculated as before. Therefore system cost is

$$C = C_{po} (1 - K_c \Delta\overline{T}_s) + (N_p - 1) (S - 2D) N_c F_c + \frac{\pi}{2} N_r F_r D + F_j P_j$$

<div align="right">(Eq. 19)</div>

If the plants are closely spaced so that S is less than 2D, then no bottom cable is used and the plants are connected by catenary risers. In this case the cost is

$$C = C_{po} (1 - K_c \Delta\overline{T}_s) + \frac{\pi}{2} N_r F_r D' + F_j P_j \qquad \text{(Eq. 20)}$$

where D' is the depth at the bottom of the catenary, assuming the catenary to be approximated by a semicircle.

Spacing Optimization. The optimum plant spacing for a park with plants distributed uniformly throughout area A_r is found by setting $dC/dA_r = 0$ and calculating the corresponding value of S.

$$A_r = \left(- \frac{1.860 \, C_{po} \, K_c \, P_e}{\eta_t \, K_s \, N_c \, F_c \, \sqrt{N_p} \, d\phi/dT_s} \right)^{2/3} \qquad \text{(Eq. 21)}$$

Note: $d\phi/dT_s$ is intrinsically negative so the term in brackets is positive.

2.3.2.2 OTEC Park Arrangements. To determine the trends of OTEC park cost with plant size and spacing, cases having several arrangements and numbers of plants are calculated. The arrangements are:

- Plants uniformly distributed throughout the resource area
- Plants clustered about six locations in the resource area
- Linear cross-current layout

For each arrangement, four different plant sizes as indicated earlier are used, always adding up to a nominal capacity of 3000 MW(e) for the park. The number of plants in each case and the supporting rational are:

- Uniformly distributed
  - 6 plants (500 MW(e) each) – hexagonal arrangement
  - 19 plants (160 MW(e) each) – one in center and two hexagonal tiers
  - 37 plants (80 MW(e) each) – one in center and three hexagonal tiers
  - 61 plants (50 MW(e) each) – one in center and four hexagonal tiers
- Clustered
  - 6 plants – hexagonal arrangement
  - 18 plants – six clusters of three
  - 36 plants – six clusters of six
  - 60 plants – six clusters of ten
- Linear
  - 6, 18, 36, 60 plants

Junctions in the uniformly distributed park are located to maximize the number of plants feeding each junction. In the clustered arrangement, there are 7 junctions, one in the center of each cluster and one in the center of the park. In the linear arrangements, there is a junction on each plant except the most remote.

The clustered arrangement is treated as a six-plant park in determining its impact on the thermal resource. The only variable is the number of risers.

Evaluation, Distributed and Clustered Plants. Values used in Eq. 21 are as follows:

$$C_{po} \quad = 6 \times 10^9 \ \$ \ (2000 \ \$/KW(e))$$
$$K_c \quad = 0.0668$$
$$P_e \quad = 3000 \ MW(e)$$
$$\eta_t \quad = 0.025$$
$$K_s \quad = 1.2$$
$$N_c \quad = 4 \ (DC \ system, \ singly \ redundant)$$

$$d\phi/dT_s = -18.7 \ \text{MW}_t/\text{mi}^2 \cdot \text{F}, \ -13.7 \ \text{MW}_t/\text{Km}^2 \cdot \text{C}$$

$$F_r = 160 \ \$/\text{ft}, \ 525 \ \$/\text{m}$$

$$D = 4,000 \ \text{ft}, \ 1220 \ \text{m}$$

$$F_j = 10,000 \ \$/\text{MW(e)}$$

Two values of F_c are used. One, supplied by DOE, assumes cable cost is independent of capacity. The other assumes the cable cost varies by a factor of two over a capacity range of 10, being equal to the DOE-supplied number at a capacity of 100 MW(e). These values are:

$$\text{(Constant)} \quad F_c = 422 \times 10^3 \ \$/\text{mi}, \ 680 \times 10^3 \ \$/\text{Km}$$

$$\text{(Variable)} \quad F_c = 106 \times 10^3 \ (P_p)^3 \ \$/\text{mi} \qquad \text{(Eq. 22)}$$

$$171 \times 10^3 \ (P_p)^3 \ \$/\text{Km}$$

The number of junctions and the value of P_j depends on the particular park arrangement. Results are tabulated for three situations:

(1) Uniformly distributed plants, constant cable cost, Table 2-17
(2) Uniformly distributed plants, variable cable cost, Table 2-18
(3) Clustered plants, Table 2-19

2.3.2.3 Evaluation, Linear Arrangement. The cost of the linear arrangement park, for the four plant sizes chosen, is calculated using the same parameter values as listed above. In addition, $\Delta \overline{T}_s$ is determined from the relations given by Fry (Ref. 1) using a current velocity of 2 kt. Under these conditions $\Delta \overline{T}_s$ is essentially zero and there is no performance change as a function of plant size. The plants are assumed to be closely spaced, and D' is taken to be the same as D. System cost as a function of plant size is presented in Table 2-20.

2.3.2.4 Electrical Transmission Summary. The cost of the 3000 MW(e) OTEC park as a function of plant size is plotted in Fig. 2-16 for the four arrangements discussed above. The cost increment over baseline plant cost represents the cost of the power collection network (cables, risers, and junction equipment), and the increase in plant cost to compensate for the depression of surface temperature T_s resulting from plant operation.

TABLE 2-17

SYSTEM COST VS. PLANT SIZE

- Plants Uniformly Spaced Throughout Resource Area
- Constant Cable Cost

N_p	N_r	N_j	Plant Power (MWe)	F_c ($/Mi) ($/Km)	A_r (Mi²) (Km²)	S (Mi) (Km)	ΔT_s (°F) (°C)	COST (normalized to 3000 MW$_{(e)}$ park)				
								Plants ($M)	Cables ($M)	Risers ($M)	Junctions ($M)	Total ($M)
6	48	1	500	422×10^3 262×10^3	9761 25281	43.4 69.8	0.66 0.37	6265	527	48	30	6870
19	144	7	160	422×10^3 262×10^3	6653 17231	20.1 32.3	0.96 0.53	6385	733	144	67	7329
37	288	13	80	422×10^3 262×10^3	5437 14082	13.1 21.1	1.18 0.66	6473	955	288	98	7814
61	480	21	50	422×10^3 262×10^3	4504 11665	9.2 14.8	1.43 0.79	6573	1118	480	140	8311

TABLE 2-18

SYSTEM COST VS. PLANT SIZE

- Plants Uniformly Spaced Throughout Resource Area
- Cable Cost Depends on Capacity

N_p	N_r	N_j	Plant Power (MWe)	F_c ($/Mi) ($ Km)	A_r (Mi^2) (Km^2)	S (Mi) (Km)	ΔT_s (°F) (°C)	COST (normalized to 3000 MW$_{(e)}$ park)				
								Plants ($M)	Cables ($M)	Risers ($M)	Junctions ($M)	Total ($M)
6	48	1	500	684 x 10^3 425 x 10^3	7073 18319	36.9 59.4	0.91 0.51	6365	727	48	30	7170
19	144	7	160	486 x 10^3 302 x 10^3	6049 15667	19.2 30.9	1.06 0.59	6425	776	144	67	7412
37	288	13	80	395 x 10^3 245 x 10^3	5562 14406	13.2 21.2	1.15 0.64	6461	901	288	98	7748
61	480	21	50	343 x 10^3 213 x 10^3	5173 13398	9.9 15.9	1.24 0.69	6497	978	480	140	8094

TABLE 2-19

SYSTEM COST VS. PLANT SIZE

- Clustered Plants
- Constant Cable Cost

N_p	N_r	N_j	Plant Power (MWe)	F_c ($/Mi) ($ Km)	A_r (Mi^2) (Km^2)	S (Mi) (Km)	ΔT_s (°F) (°C)	COST (normalized to 3000 MW(e) park)				
								Plants ($M)	Cables ($M)	Risers ($M)	Junctions ($M)	Total ($M)
6	48	1	500	422 x 10^3 262 x 10^3	9761 25281	43.4 69.8	0.66 0.37	6265	527	48	30	6870
18	192	7	160	422 x 10^3 262 x 10^3	9761 25281	43.4 69.8	0.66 0.37	6265	527	192	60	7044
36	336	7	80	422 x 10^3 262 x 10^3	9761 25281	43.4 69.8	0.66 0.37	6265	527	336	60	7188
60	528	7	50	422 x 10^3 262 x 10^3	9761 25281	43.4 69.8	0.66 0.37	6265	527	528	60	7380

TABLE 2-20

SYSTEM COST VS. PLANT SIZE

● Linear OTEC Park Arrangement

| N_p	N_r	N_j	Power Plant	ΔT_s	COST (normalized to 3000 MW$_{(e)}$ park)			
					Plants	Risers	Junctions	Total
			(MWe)	(°F) (°C)	($M)	($M)	($M)	($M)
6	40	5	500	0.0 0.0	6000	40	70	6110
18	136	17	160	0.0 0.0	6000	136	243	6379
36	280	35	80	0.0 0.0	6000	280	504	6784
60	472	59	50	0.0 0.0	6000	472	885	7357
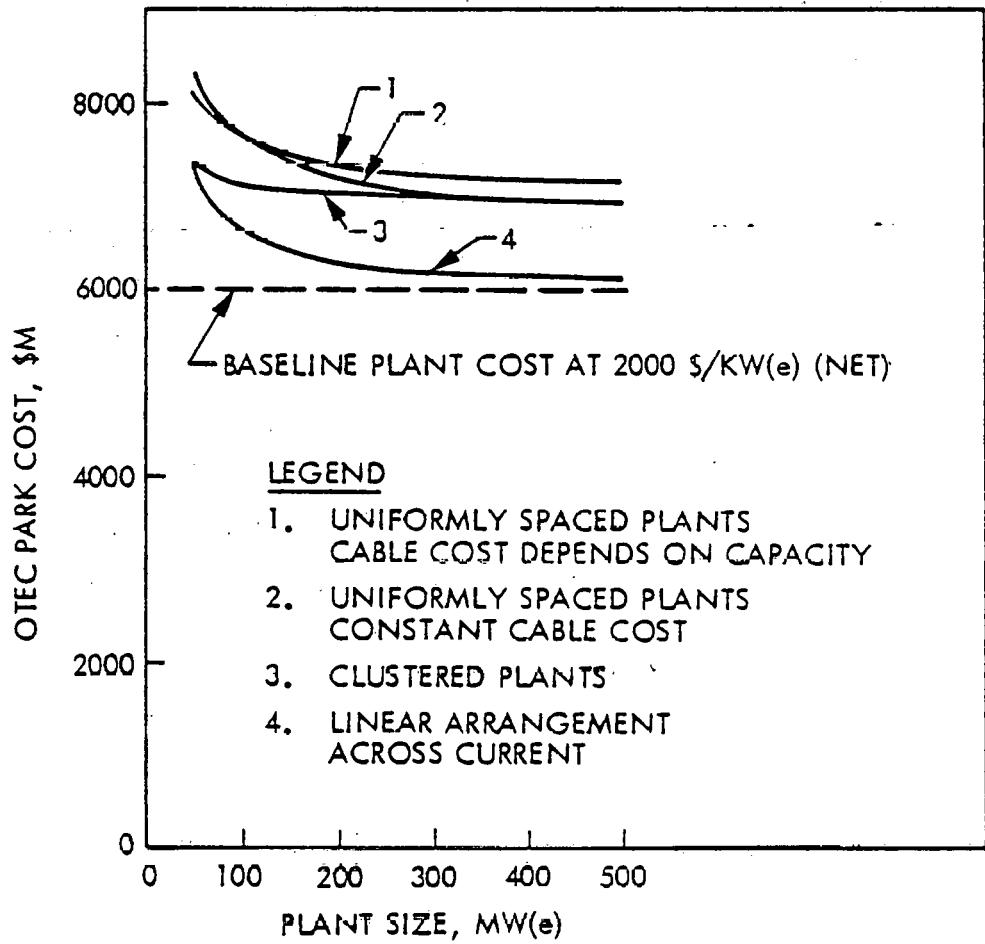
Fig. 2-16 OTEC Park Cost as a Function of Plant Size

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It is evident that a plant size of 150 to 200 MW(e) is sufficient to provide most of the benefit of scale with regard to the electrical energy transfer system. The final selection of the preferred plant size range must, of course, also include the effect of plant construction and position keeping costs as functions of plant size.

Some comparison of the four arrangements is in order. The linear arrangement which takes advantage of a unidirectional current has the lowest cost because it has no bottom cables. In the presence of any appreciable current (say 1/2 kt or greater) the plants can be closely spaced, connected by a series of catenary risers. System costs increase for small plant size because the number of plants in the park increases inversely as plant size, with proportional increase in number of risers and geometric increase in required junction equipment capacity.

The clustered arrangement has the next lowest cost. The cost is relatively independent of plant size because the bottom cable and junction arrangement, and depression of ocean surface temperature, are essentially the same in all cases. The dependence of cost on plant size reflects mainly the increase in the number of risers with the smaller, more numerous plants.

The comparison of the two highest cost curves, for arrangements of plants uniformly spaced throughout the park area, illustrates the effect of the two assumed cable cost relations (constant cost and cost dependent on cable capacity). As expected, the assumption that cable cost depends on capacity, in this case capacity to the 0.3 power, tends to flatten the curve of cost versus plant size.

2.3.2.5 <u>Impact of Chemical Conversion Energy Transfer.</u> The impact of chemical conversion energy transfer on configuration selection is considered in terms of

- Adequacy of plant layouts to contain conversion equipment or their suitability to be modified for such purposes.
- Adaptability of plants to the "grazing" mode, in which they would cruise about slowly, following the location of the highest thermal gradients.

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The procedure is to compile requirements on deck area, volume, and weight for a typical chemical conversion plant, tabulate the equipment containment characteristics of the current configuration layouts, assess adequacy for equipment containment and grazing, and recommend modifications where necessary.

Requirements.   A 100-MW(e) liquid ammonia plant is selected as typical of the equipment which would be contained in an OTEC plant for chemical conversion. The deck area, volume, and weight of this equipment, using current state of the art, is presented in Table 2-21.

Table 2-21

EQUIPMENT SIZE AND WEIGHT FOR 100 MW(e) AMMONIA PLANT (REF. 3)

Item	Deck Area (ft^2) (m^2)	Volume (ft^3) (m^3)	Weight (Ton) (metric ton)
Power Conditioning	1,200 111	21,600 612	132 60
Desalination	936 87	13,104 371	50 23
Electrolyzers (Lurgi type)	19,102 1,775	193,292 5,473	2,945 1,339
Air Separation Unit*	1,926 179	54,606 1,546	130 59
Ammonia Synthesis Loop*	3,880 360	21,874 619	418 190
Total	27,044 2,512	304,476 8,622	3,675 1,670

* Includes work-around space for installation and maintenance equal to 50% of number quoted.

Platform Characteristics.   The characteristics relative to chemical conversion plant containment, for the six configurations as currently defined, are presented in Table 2-22.

Table 2-22

PLATFORM EQUIPMENT CONTAINMENT CHARACTERISTICS

Configuration	Available Deck Area (ft^2) (m^2)	Available Height (ft) (m)	Comment
Ship	91,978 8,545	Equipment placed on present weather deck, height restricted by crane and helicopter landing clearances.	Ammonia vapor piping intrudes into above-deck space. Remaining space is adequate.
Circular Barge	28,923 2,687	Equipment placed on present weather deck, height restricted by crane and helicopter landing clearances.	Locating plant in unused area on existing layout.
Semi-Submersible	143,440 13,326	Equipment placed on present weather deck, height restricted by crane and helicopter landing clearances.	Requires decking in present open trusswork area.
Tuned Sphere	—	—	Above-water deck area not detailed on layout.
Submersible	—	—	Present layout shows 9m diam. column at waterline topped by four decks 25m diam. × 3.21 interdeck height, with space for accommodations and plant machinery only.
Spar	—	—	Present layout shows 30m diam. column above water-line with space for accommodations and plant machinery only.

Assessment. In all cases, the weight of equipment is small compared to platform weight, so can be included without penalty to capacity or stability. In some cases the added weight of chemical conversion equipment is an advantage since it reduces the need for inert ballast.

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The ship, circular barge, and semi-submersible are all adequate as configured, having sufficient available deck area and volume. The other three configurations will require addition of space for the chemical conversion plant.

Minimum motions in seas is an asset in chemical conversion plant operation. Motions may interfere with the functioning of equipment where liquid levels or orientation are important, or may impede transfer of product to a pipeline or barge. However, no quantitative requirements have as yet not been defined in this area. As a result, smaller motions can be used as a factor in selecting the best of two configurations which are otherwise equal, but no broader judgements can be made.

The suitability for grazing operation is evaluated in terms of the percentage of plant net output consumed in cruising at a speed of 1 kt in still water. The power requirements are scaled down from the 3 kt and assume a thruster motor efficiency of 90%. The results are plotted in Fig. 2-17. They show that the ship, circular barge, and semi-submersible are about equivalent, with the submersible, sphere, and spar requiring higher power. The cost penalty associated with grazing can also be calculated as the product of total plant cost times the percentage plotted in Fig. 2-17.

Recommended Modifications. The chemical conversion plant, for safety reasons, must be contained in a non-submerged compartment or on an open deck. The ship, circular barge, and semi-submersible are adequate in this regard as currently configured. It is suggested that the containment can be within a disk-shaped structure, as shown in Fig. 2-18a, which can be appended to each of the other three configurations as shown in Fig. 2-18b. The tuned sphere and spar as now configured have adequately stout structures to support the added load. The submersible, however, has a waterline column of 9m diameter, which is probably too slender to support the super-structure. It is suggested that this column be divided into four columns of 4.5m diameter at a centerline spacing of 11.0m, providing added structural strength while keeping the same waterline area.
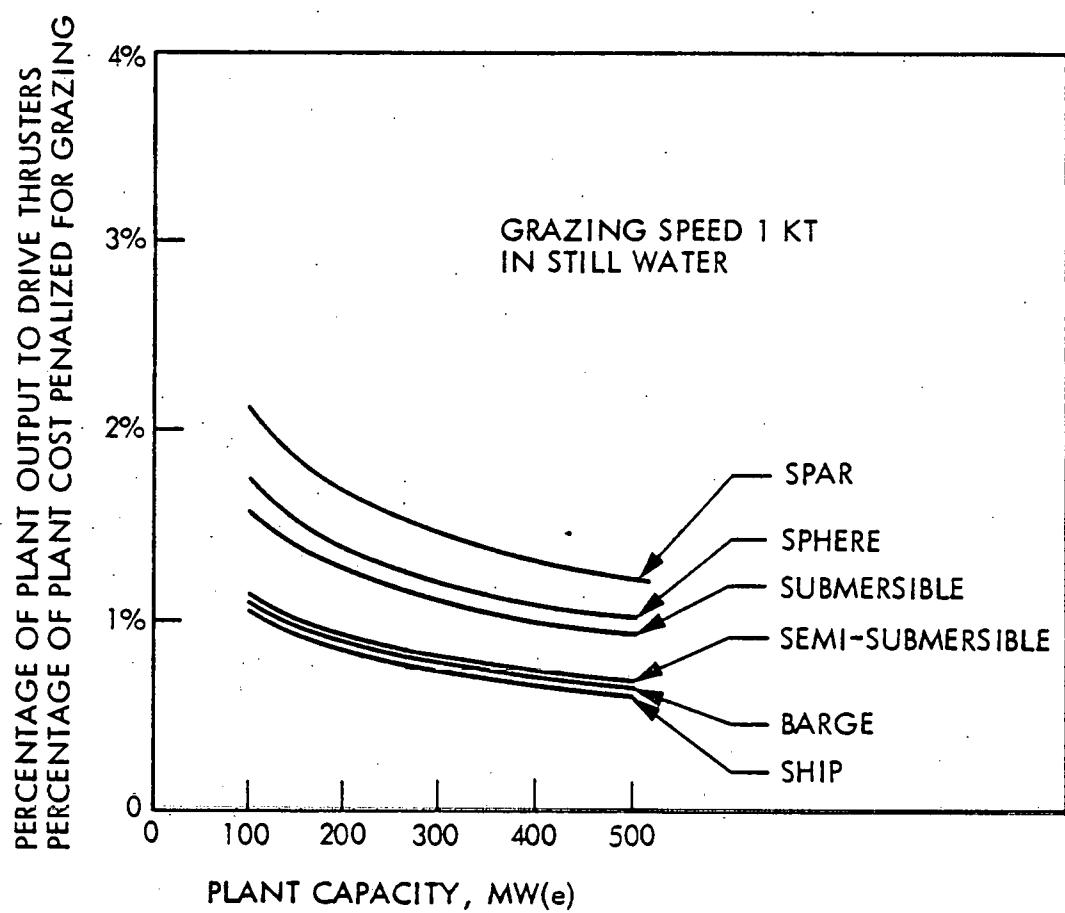
Fig. 2-17 Power and Cost Penalty for Grazing

CREW
ACCOMMODATIONS

34 FT
10.3 m

AMMONIA PLANT

142 FT DIA
43.3 m
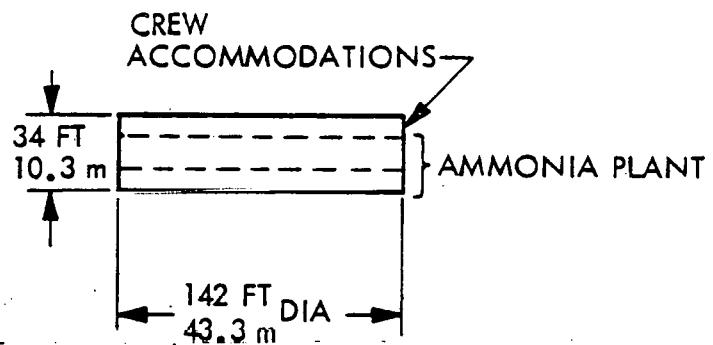
(a) Dimensions of Containment Space

100 FT   50 m

TUNED
SPHERE

SUBMERSIBLE

SPAR
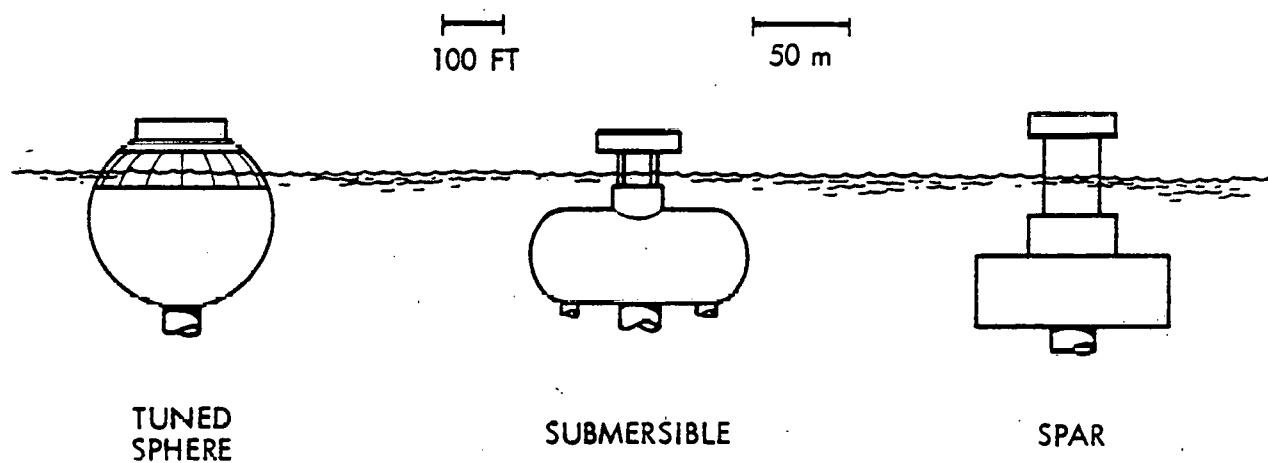
(b) Installation on Platform Configurations

Fig. 2-18 Suggested Chemical Conversion Plant Containment

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2.3.2.6 <u>Evaluation of the APL Plant Ship Concept.</u> The John Hopkins University applied Physics Laboratory (APL) has designed a 100 MW(e) ammonia manufacturing plant ship around twenty of their five MW(e) power modules, which use the "trombone" type heat exchanger. This design is evaluated in comparison with the ship configuration prepared for this study. The main characteristics of the two concepts are listed in Table 2-23.

Table 2-23

COMPARISON OF APL PLANT SHIP DESIGN WITH
STUDY SHIP CONFIGURATION

Hull Material	APL Design Reinforced Concrete	Study Configuration	
		Mild Steel	Reinforced Concrete
Length (m)	145	165	171
Beam (m)	60	66	71
Draft (m)	26	25	27
Weight (MT)			
Hull and Structure	36,800	40,000	153,400
Cold Water Pipe	12,200	56,800	56,000
Displacement (MT)	128,800	274,000	329,900
Cost ($M)			
Platform[a]	29	174	107
Cold Water Pipe	6.3	10[b]	10[b]

(a) Includes all items except power system and ammonia.
(b) Designed for sea states at Brazil site.

The APL platform is smaller than the study configuration. This is the result of using the "trombone" type heat exchanger which lends itself to compact packaging and short, direct seawater flow paths. The heat exchangers are contained in trunks, open at top and bottom, which are integrated into the platform structure. Water-tight compartments comprise a relatively small portion of the total hull volume. The site is relatively benign, with a maximum expected sea state of six. As a result, the concrete

weight of the APL design is considerably less than that of the study concept, which is a generalized design suitable for various heat exchanger types and sites.

The APL platform appears structurally sound. It is compartmented to give good strength and rigidity, and can be assembled from modules, avoiding the need for extraordinary construction facilities. The assumptions made in the static stability analysis appear valid, and presumably the analysis was done correctly. However, for the dynamic analysis a rigid cold water pipe attachment was assumed and elasticity in the cold water pipe was ignored. As a result the analysis is questionable in two areas.

- The bending moments and shear at the platform/cold water pipe interface may not be properly estimated.
- The effects of cold water pipe elasticity on platform stability are not included. Excitation of elastic nodes in the cold water pipe can greatly amplify loads and motions for both platform and pipe.

Thus, the cold water pipe design may be inadequate both structurally and in provision for deployment and attachment.

The APL cost estimates for the platform are comparable, on a weight-for-weight basis, with costs used for concrete in this study. However, the $6.3M estimate for the cold water pipe is in the range of recent estimates for the 1-MW(e) OTEC-1 cold water pipe, so certainly must be low for a 100-MW(e) capacity pipe, considering even the cost advantages of concrete over other materials.

In summary, the APL design is a good integration of the platform with their particular power system, and is sound from the structural, stability, and producibility standpoint. However, the analysis and design of the cold water pipe may be inadequate and its cost estimate appears to be unrealistically low.

2.3.2.7 Summary. All of the configurations are suitable as platforms for chemical conversion energy transfer, either as presented or with the suggested modification to add containment space. All other things being equal, the platform with the least motion

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in seas is the most desirable. Existing requirements on motions are not well enough defined to provide a more definitive criterion. In grazing operation, the ship, circular barge, and semi-submersible have the smallest thruster power requirement, with the others requiring up to twice the power.

2.3.2.8 References.

1. Carnegie-Mellon University, Department of Civil Engineering, Effects of Oceanic Flow Patterns on the Thermal Efficiency of Ocean Thermal Energy Conversion (OTEC), by D. J. Fry, C00/2895-3, Pittsburgh, Pa., Apr 1976

2. University of Hawaii, Department of Ocean Engineering, A Further Evaluation of the Oceanographic Conditions Found Off Keahole Point, Hawaii, and the Environmental Impact of Nearshore Ocean Thermal Energy Conversion Plants on Subtropical Hawaiian Waters, by Karl H. Bathen, Nov 1975

3. Institute of Gas Technology, IIT Center, Optimization Study of OTEC Delivery Systems Based on Chemical-Energy Carriers, by Alex J. Konopka, Abu Talib, Bernard Yudow, and Nicholas Biederman, ERDA/NSF/00033-76/T1, Chicago, Ill., Dec 1976

2.3.3 Seawater System

The seawater system is the second most significant subsystem of the platform in cost, size, and impact on the net power output of the plant. The following five subsystems have been analyzed and design guidelines have been developed for incorporating them in the platform.

(1) Cold water pipe

(2) Seawater pumps

(3) Platform/CWP transition

(4) Water ducts

(5) Biofouling/corrosion control

The optimum plant integrates these components with each other and with the hull and power systems within the constraints of the platform. Because of the large portion of the platform devoted to the seawater system, it is necessary to optimize the size, cost, and performance of all elements of the system. This section identifies the characteristics of the most satisfactory design of the major elements of the seawater system.

2.3.3.1 <u>Cold Water Pipe.</u> The cold water pipe (CWP) conducts cold seawater to the cold water plenum in the OTEC platform and is therefore an essential element of the Seawater System. The pipe extends from a depth dependent on the site temperature profile to the platform/CWP transition depth, which varies with platform type.

A baseline design concept and alternative approaches are presented in this section. Design features, including size, material, loads, structure, construction, and deployment are presented to (1) demonstrate concept feasibility and (2) to illustrate design variability between candidate platforms and sites. CWP variability is incorporated in the evaluation process, thereby allowing discrimination between platforms.

<u>Cold Water Pipe Size.</u> The diameter is the sum of inside diameter based on required seawater flow rate and structural wall thickness, while the length is the difference between inlet depth based on seawater temperature difference requirement and depth of hull/CWP transition.

A review of the temperature difference profiles for the five candidate sites (Ref. 1) reveals a wide variation with site and season. The fraction of time during which delta temperature is below a minimum of 16.7° C and above a desired operating level of 22.2° C at depths of 600m and 1000m is reviewed. At 1000m depth the desired delta temperature is available at least half time at three sites, and quarter time at two sites. Further, the minimum temperature is exceeded all year at all sites except New Orleans. The desired delta temperature is not available at 600m depth except at the Brazil site where it is available quarter time. Therefore, 1000m depth is selected as the requirement for cold water inlet depth. This requirement is assumed to be independent of platform net power output.

Site	Percent of Time Below 16.7°C ΔT		Percent of Time Above 22.2°C ΔT	
	600 m	1000 m	600 m	1000 m
Hawaii	0	0	0	25
New Orleans	38	17	8	29
Puerto Rico	21	0	0	58
Key West	31	0	0	45
Brazil	0	0	25	58

LOCKHEED MISSILES & SPACE COMPANY. INC.

The inside diameter, determined by required flow rate, is obtained by an optimization program which seeks minimum life-cycle costs for seawater pumps, pipe, and power. The optimum inside diameters for 100, 200, and 500-MW(e) (net) output are 16.4, 22.7, and 34.9 m, respectively. The flow rates associated with these sizes are 5.7×10^3, 11.4×10^3, and 28.4×10^3 m^3/sec, respectively. The wall thickness is dependent on CWP material and loading. Based on results of analytical studies for concrete pipe, a wall of 0.61 m was selected to provide sufficient bending strength under dynamic loading in severe seaways. The resultant thickness-to-diameter ratio of 0.037 held constant, yields outside diameter of 17.6, 24.4, and 37.5 m.

Cold Water Pipe Material. Several candidate materials presently under investigation in various OTEC studies are concrete, glass reinforced plastic, steel, aluminum, and rubber. Steel reinforced precast concrete is selected for its high weight, large outside diameter of pipe, low maintenance, and potentially low cost (Ref. 2). The first two features cause concrete CWP to have a greater impact on platform requirements (greater buoyancy, large diameter of CWP/hull interface) than lighter pipes of alternate materials. Consequently, greater data range is provided for platform discrimination.

Material properties include modulus of elasticity equal to 3×10^6 psi, density of 150 lb/ft^3, and maximum compressive strength of 5000 psi for reinforced concrete.

Cold Water Pipe Loads. The CWP is loaded statically by its own weight, by the seawater moving inside, externally by the current, at the upper end by the platform, and by wave action. The primary loading is shown to be loads induced on the CWP by wave forces on the platform. These dynamic loads are dependent on platform motion response; heading; wave severity; depth of pipe attachment; pipe material, size, and stiffness; and of the platform/CWP interface. The sensitivity and trend of these loads to parameter variations is summarized in this section. A linear superposition of stresses for a specified loading case indicates the significance of dynamic bending stress with respect to resultant stress.

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The maximum bending moment occurs on the CWP at different depths depending on pipe material, platform, and other parameters. This moment characterizes the CWP dynamic loading condition and is used to illustrate the influence of pipe material and wave height (Fig. 2-19). The amplitude of peak moment is approximately two to three times the significant values; while the significant value is four times the rms moment. Moment is seen to increase with wave height from the sea state 6 condition to the 100-yr storms at the candidate operational sites by a factor of 10 in one case. The moment on the aluminum case exceeds that on the GRP and concrete pipe with segments. The concrete pipe without joints experiences the largest moment, five times the segmented pipe moment. With exceptions moment is lowered by reducing material modulus.

Bending stress is seen to be lowest for the segmented concrete CWP and highest for aluminum (Fig. 2-20). However, allowable stress levels are higher for aluminum. The segmentation reduces stress levels by a factor of 4. The range of stresses in CWP attached to the six different platform types is 0.9×10^3 psi to 1.47×10^3 psi, with the semi-submersible producing the lowest stress and the circular barge the highest for a segmented concrete pipe of 2-ft wall thickness for a significant wave height of 45.8 ft. The spar with a high attachment point (60 m depth vs. 115 m) has a 45% lower bending stress. This indicates the desirability of optimizing the height of the attach point. Heading of the ship, semi, and submersible platforms also affects dynamic bending stress in the 100-year storm conditions. Therefore, heading control in extreme condition is one approach to minimizing stresses and pipe wall thickness.

Maximum significant shear force increases with wave height and varies with CWP material in a manner similar to the variation of bending moment (Fig. 2-21). The effect of increasing pipe wall thickness generally decreases maximum stress if the thickness is increased significantly, otherwise the stress may actually be higher for a CWP with larger wall thickness. This may be attributed to higher pipe stiffness and resonance with a lower modal period with increasing thickness.
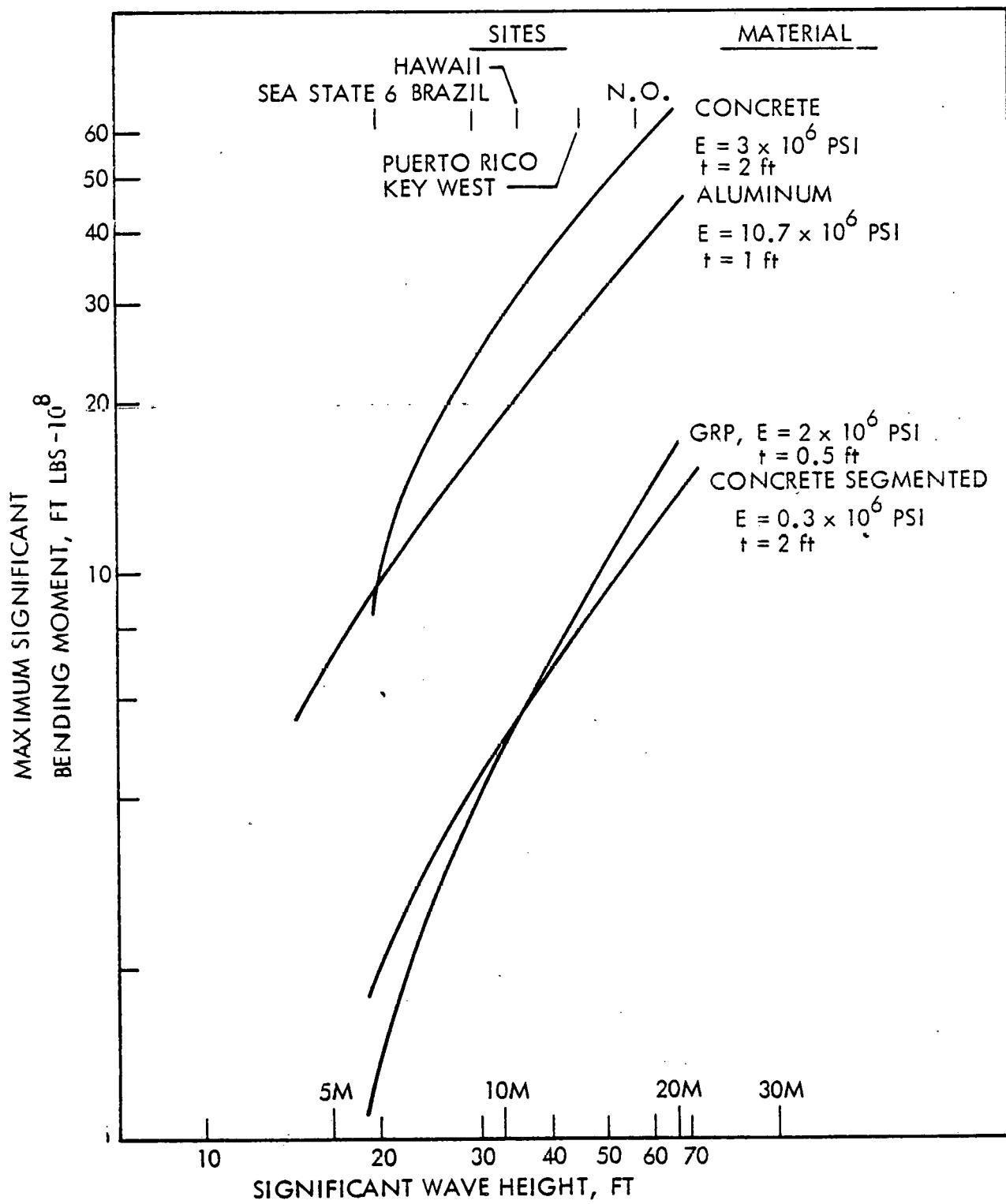
Fig. 2-19 Influence of CWP Material on Maximum Significant
Dynamic Bending Moment — 100-MW(e) Net Spar

2-70
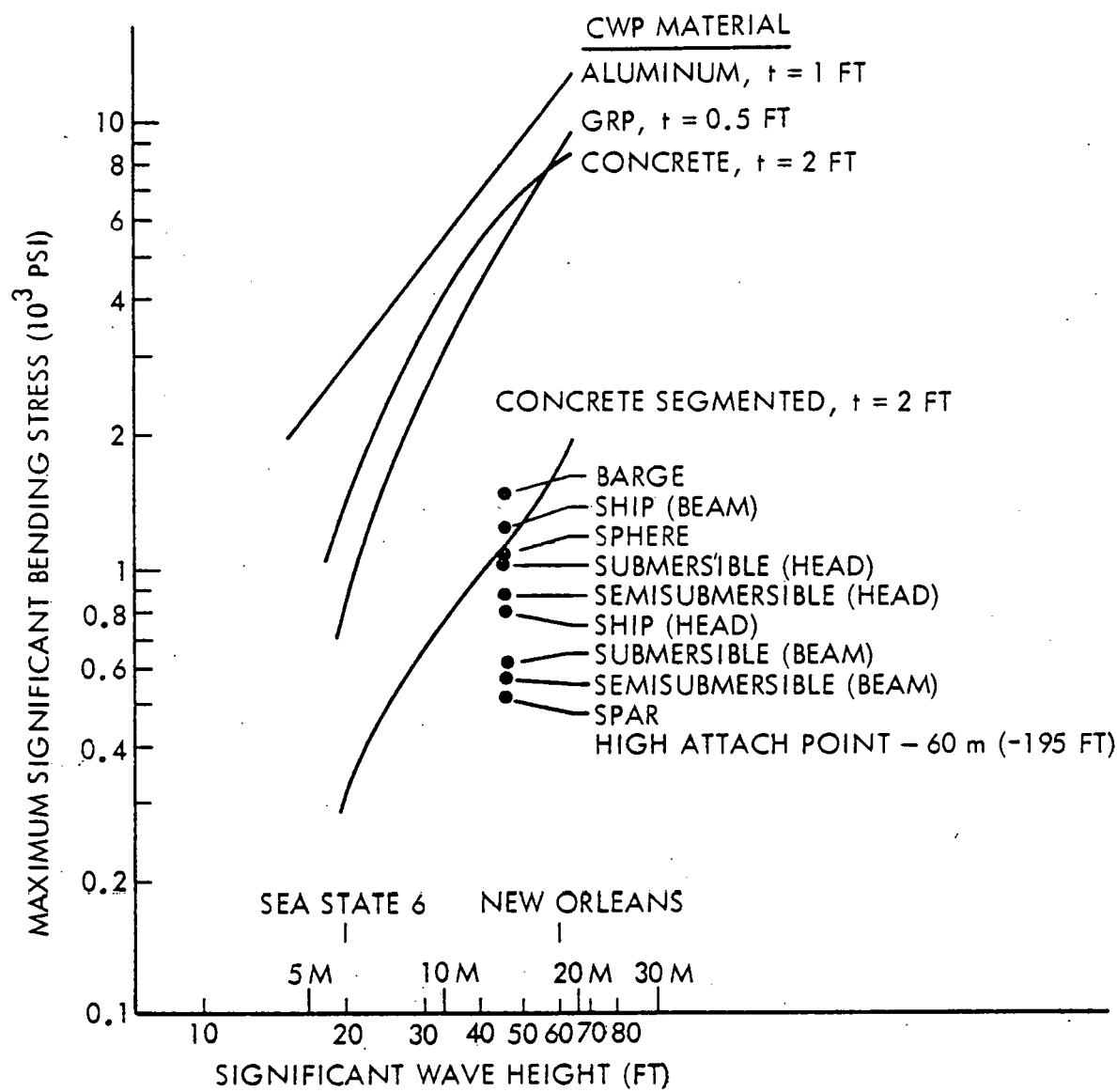
Fig. 2-20   Influence on CWP Material on Maximum Significant
Dynamic Bending Stress — 100-MW(e) Spar

2-71
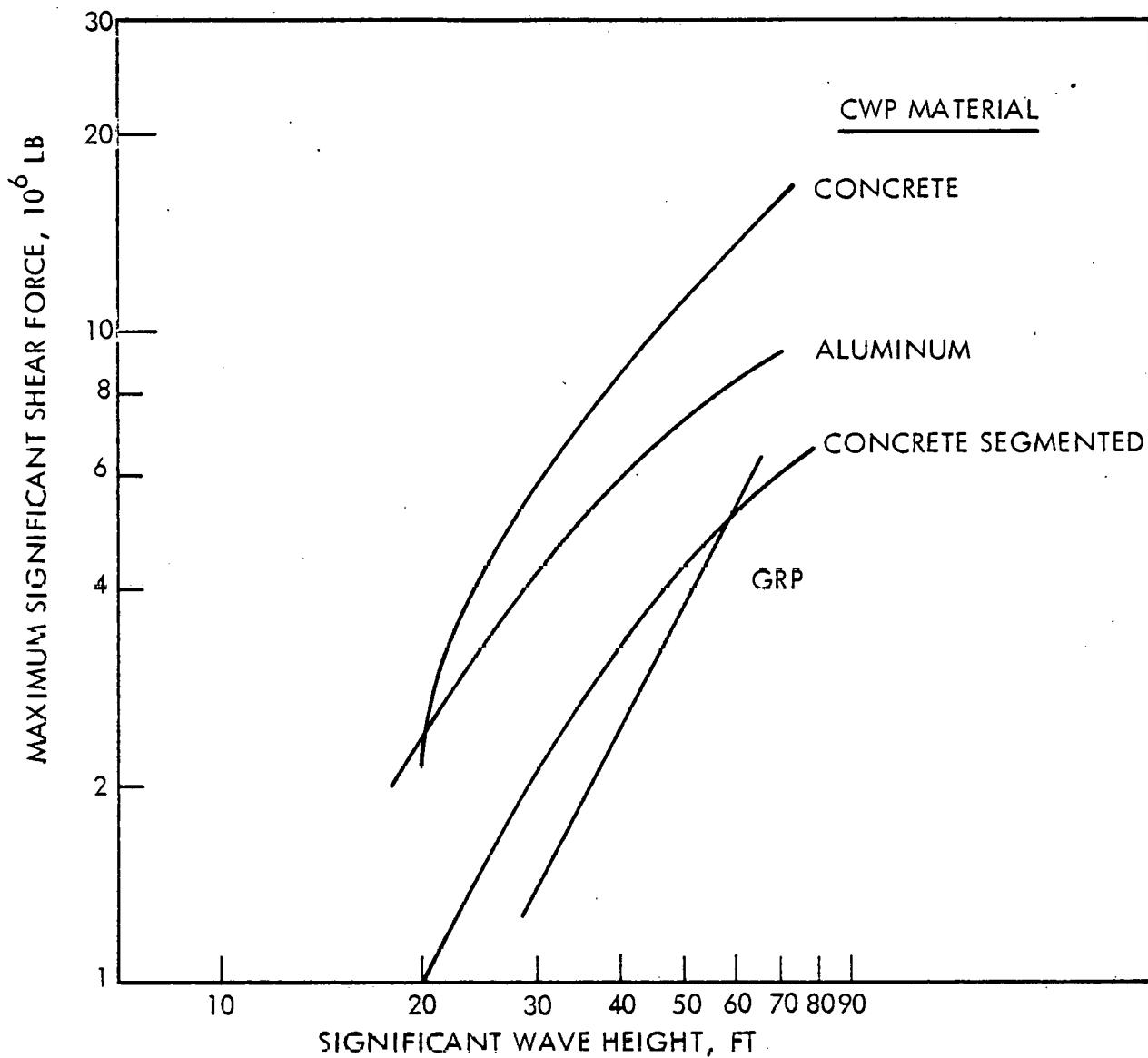
Fig. 2-21 Variation of Maximum Significant Shear in CWP With
Wave Height and Pipe Material — 100-MW(e) Spar

A stress analysis of the baseline 100 MW(e) (net) CWP concept including both static
and dynamic loads reveals the variation of resultant stresses. Loads include static
weight, current shear and moment, dynamic shear, moment and axial force due to
platform and wave forces, and pressure differential. Stresses at three depths where
CWP dynamic moments are high were computed for the ship in a six knot current,
quartering seas, 100 year storm in New Orleans. The results are summarized in
Table 2-24. At the attachment depth of 13.6 m the dominant stress component is
axial tension due to pipe weight, while at 121 m depth the dynamic bending stress is
57 percent of the resultant stress.

Table 2-24

STRESS ANALYSIS OF CWP

100-MW(e) Ship, New Orleans, 6-Knot Current, Concrete CWP, 0.3×10^6 psi
Stiffness of attachment to platform = 10^9 in roll & pitch. H_s = 17.7m (58.1 ft)

Depth (m)	Static Stress (psi)				Dynamic Stress (psi)			Resultant (psi)	Safety Factor on Ultimate
	Axial	Shear	Bending	Hoop	Axial	Bending	Shear		
13.7	1105	33.5	238.4	21.0	121.5	191.7	70	1663	3
122.0	967	5.7	0.5	18.0	106.0	1453.0	31.6	2527	2
367.0	145	0.1	0	2.8	16.0	1500.0	20.5	1651	3

The necessary thickness of the wall of the pipe has been estimated for two platforms (barge and spar) to meet the requirements for the dynamic bending stress with an approximate consideration for the other pipe stresses.

The estimated wall thickness increases rapidly with significant wave height. The lower limit for wall thickness in low sea conditions is dictated by buckling criteria for the CWP (Ref. 2) for both stiffened and unstiffened pipe structures, Fig. 2-22. The glass reinforced plastic (GRP) pipe requires the smallest wall with the flexible joint, segmented concrete requiring the thickest. There has been extensive extrapolation of the principal data to derive these results. However, the trends are reasonable and the magnitudes are certainly representative of the needed wall thicknesses. Refinements to the CWP design solution, as illustrated by the two foot thinner wall resulting from the raised attachment of the concrete pipe to the spar, are needed in the final optimizing of the pipe, platform and power systems. At this point, it is sufficient to note that the cost of material for the cold water pipe is highly variable. It changes with site since survival in the extreme local storm is the design criteria for the CWP.
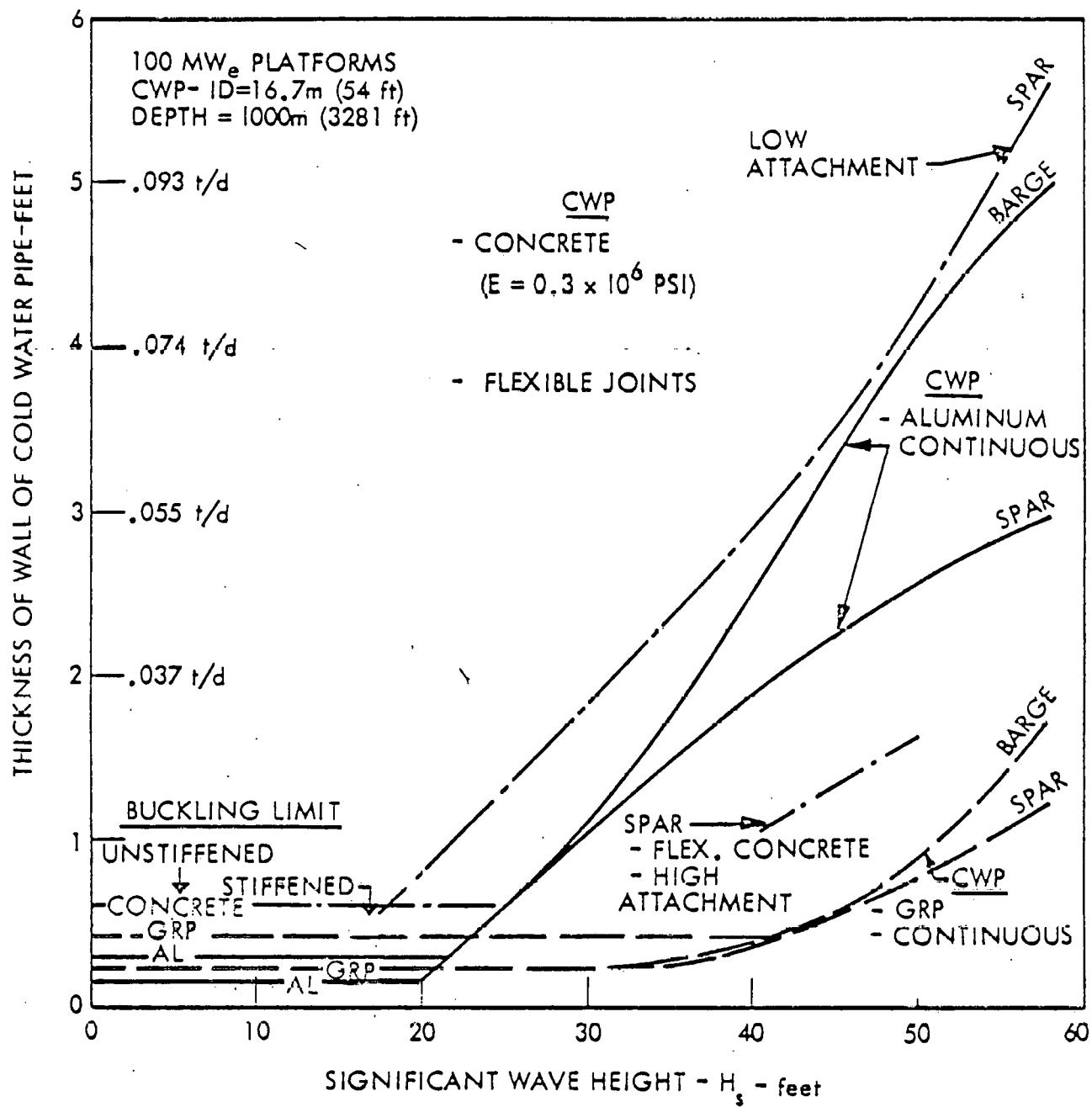
Fig. 2-22 Wall Thickness of CWP for 100-MW(e) Platforms
as Functions of Significant Wave Height

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The effects of platform on the CWP are evident as these two example platforms require widely differing wall thickness (3 ft vs 5 ft for two platforms with aluminim pipe). Other platforms cause smaller dynamic bending stresses and require an even wider range of wall thickness.

Costs have been derived for steel reinforced concrete pipe and these have been extended to estimate costs of these pipes of varying wall thickness, Table 2-25. The importance of platform induced loads on the cost of this subsystem is emphasized by the 2.4 to 1 range in costs for each site and a 2 to 1 range in cost among these four sites. Those platforms having high costs for this design would be modified downward by an optimization with the power system loading to a smaller diameter pipe and/or a shorter length pipe. It should be observed that the estimated cost for the CWP on the barge at New Orleans is 85 percent as costly as the concrete structure of this barge.

Cold Water Pipe Structure. The cold water pipe is a thin-walled shell of reinforced concrete material. Characteristics of the baseline design concept are identified in Table 2-26 for a 100 MW(e) (Net) plant output.

Table 2-25

ESTIMATED COSTS FOR FLEXIBLE JOINTED CONCRETE COLD
WATER PIPE, BOTTOM AT 1000 METER (3,281 FT),
E = 0.3 × 10^6 PSI, 100 MW(e) (NET) CAPACITY

Site	Hawaii ($M)	Key West, Puerto Rico ($M)	New Orleans ($M)
Significant Wave Height	35.9	45.8	58.1
Platform Type			
Ship (Beam)	23.3	33.5	47.0
Barge	16.3	24.1	37.3
Semi	16.5	23.1	31.6
Tuned Sphere	21.3	24.3	39.2
Submersible	20.3	27.6	36.8
Spar - high attachment	9.4	13.2	19.6

Table 2-26

COLD WATER PIPE BASELINE DESIGN

Characteristic	Net Power Output (MW(e))		
	100	200	500
Depth of Lower End (m)	1000	1000	1000
Depth of Upper End (m)	25-120	25-120	42-133
Length (m)	880-975	880-975	867-958
Inside Diam. (m)	16.4	22.7	34.9
Length/ID	60	43	27
Thickness/ID	0.037	0.037	0.037
Wall Thickness (m)	0.61	0.84	1.29
Outside Diam. (m)	17.6	24.4	37.5
Weight/Unit Length (LT/Ft)	17.67		
Weight/Unit Length in Water (LT/Ft)	7.62		
Concrete Volume, Yd^3/Ft	9.77	19.0	44.7
Concrete Pipe Cost, $M			
Spar with High Attachment			
Designed for N.O. (H_s = 58.1 ft)	19.7	41.2	95

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The pipe consists of a series of sections joined with structurally continuous bearings such as neoprene rubber. The top of the upper section is flanged to distribute the CWP weight onto the hull/CWP interface bearing (Section 2.3.3.3). To reduce the weight, the wall of each section has 25-percent void spaces. The inner and outer surfaces are unobstructed by stiffeners. Steel reinforcing tendons provide axial and circumferential prestressing. Subsections are precast in a shore facility in 15-m lengths. This is accomplished by slip-forming vertically oriented subsections. Three subsections are then assembled by gluing the ends together and post-tensioning the now completed 45-m-long section in the horizontal position. Each section (2650 tons) is then lifted by overhead crane aboard a barge for towing to the operational site where final assembly of the CWP is completed.

The joint connects each 45-m section together to form a continuous pipe. The joint provides a method of CWP installation and a means to reduce seaway-induced peak bending stresses in the pipe. Based on the analytical prediction of bending stresses, a preliminary estimate of joint rotational stiffness is 1×10^9 ft-lb/radian. On-going analytical effort will provide further guidelines on the significance of segment length and joint axial and rotational stiffnesses in reducing CWP stresses.

The joint design concept shown in Fig. 2-23 will provide stiffnesses in the range required. The joint consists of an elastomeric element of 17.7-m OD, 16.5-m ID and 1.5-m length. The steel ring assembly is prefabricated and installed on each pipe section.

An element of 40 Shore hardness will experience a 40-psi shear stress at the upper section of the CWP under static conditions and will rotate a maximum of 2 deg as shown. This level of rotation adds an average of 25 psi stress to the extending side. The angular stiffness of this design is approximately 4×10^9 ft-lb/radian, and axial stiffness is 7×10^7. The rubber in the upper pipe sections is stressed to 1000 psi tension. Alternate materials for these sections will be sought. The equivalent modulus of a non-segmented CWP having equal deflection is 0.3×10^6 psi.

ANGULAR DEFLECTION

AXIAL LOAD DEFLECTION

STEEL RING

4.0 M

1.5 M

BONDED

2 DEG

16.5 M

17.7 M
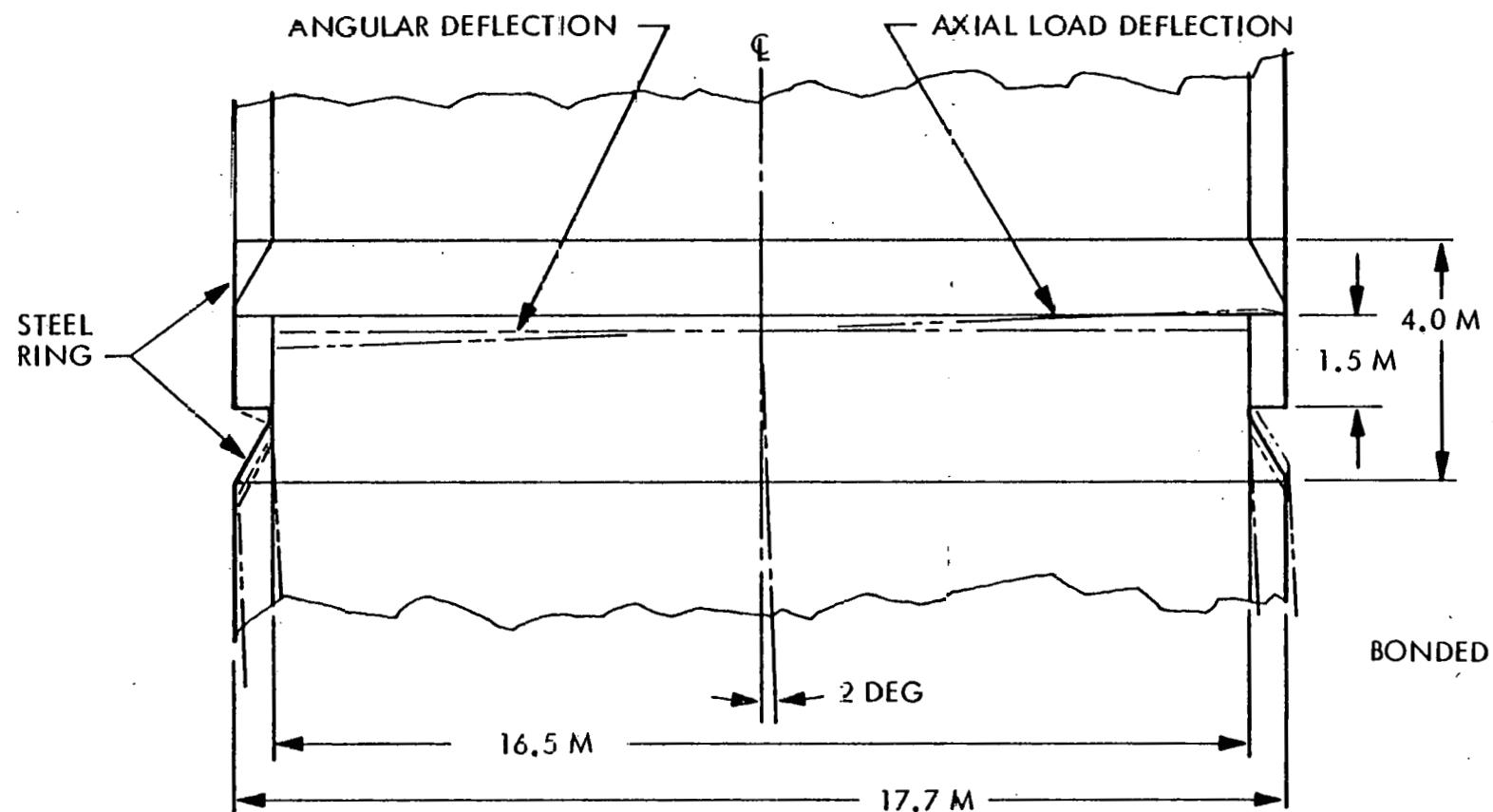
Fig. 2-23 Cold Water Pipe Joint Concept

Cold Water Pipe Assembly and Installation.   The CWP installation sequence is pre-
sented in this section.   Features of the pipe, equipment required, sequence of steps,
and duration of process are presented.   Costs for deployment and installation of the
CWP including the effect of platform size, type, and site are treated.

The pipe sections are towed on a barge to the moored platform at the operational site.
The barge is rafted to a crane vessel which in turn is rafted to the OTEC platform
(see Fig. 2-24).   A ring structure consisting of hydraulic jacking equipment is
assembled in the platform center well on a temporary spacer structure. The concept-
ual design of this system is based on data (provided by Earl and Wright) which is
indicative of state-of-practice in offshore oil jackup rigs.   The largest of these rigs
is approximately 25,000 mt.   There are twelve hydraulic cylinders of 2-m diam. and
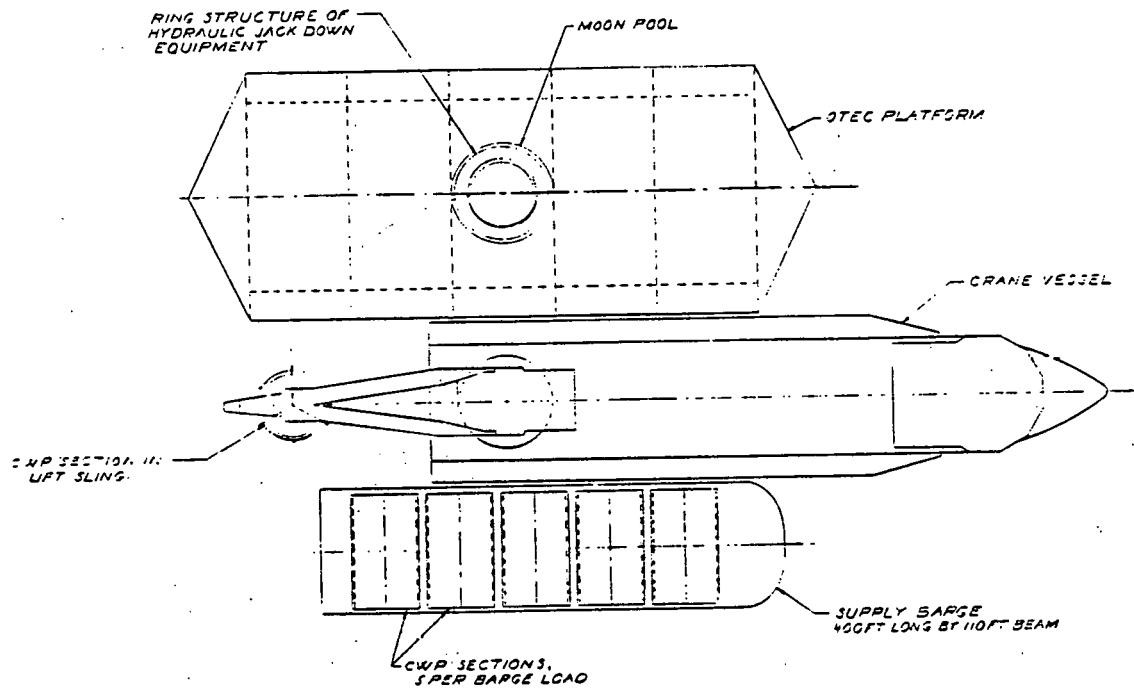
Fig. 2-24   CWP Section Supply and Handling Arrangement

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3.6-m stroke. Each cylinder connects an upper and lower segmented ring and each ring contains 24 gripping shoes. A control system providing semi-automatic operations yields equal, continuous hydraulic operation.

The assembly and installation sequence for the CWP on a 100-MW(e) (net) ship platform is illustrated in section views in Fig. 2-25. All platform designs feature a center well for CWP installation following this procedure. The first CWP section is hoisted and levered into the center well by the crane with a 3-point sling assembly with the jacking cylinders extended (Step 2). Depending on platform type and size, as well as site, an onboard overhead crane may be required in addition to the crane on the crane vessel rafted to the platform. With the first section supported by the lower ring, the second pipe section is positioned above the first, using the upper ring for position control (3), and the elastomeric joint is bonded onto the lower section (4). The bonding takes place above the waterline. Upon completion of curing, the two-section assembly is lowered, the lower ring assembly holds the pipe, and sequences (3) and (4) are repeated until the required assembled CWP length, less one section, is completed.

At this stage a ring of sabot blocks is installed on the upper deck on the center well rim. The final CWP section, with upper flange, is lowered onto these blocks and the joint completed. The jacking structure is removed from the well and relocated onto supporting structure on the main deck. The elastomeric bearing blocks comprising the platform/CWP interfaces are positioned below the waterline.

The lower ring shoes hold the CWP while the upper ring is extended to receive a section of CWP. This section serves as a lowering fixture and is bolted to the upper end of the CWP (6). The final lowering operation is completed by alternate gripping by the upper and lower rings until the flange is seated on the elastomeric bearing. The fixture joint is de-bolted, removed and reaction rings are installed above the upper bearing columns to preload these blocks. The CWP is thereby assembled and installed (7).

To accomplish the lowering operation using the hydraulic grip shoes, lifting grooves are required in the CWP outer wall (see Fig. 2-26). This groove pattern is formed during the pre-casting operation of section segments.
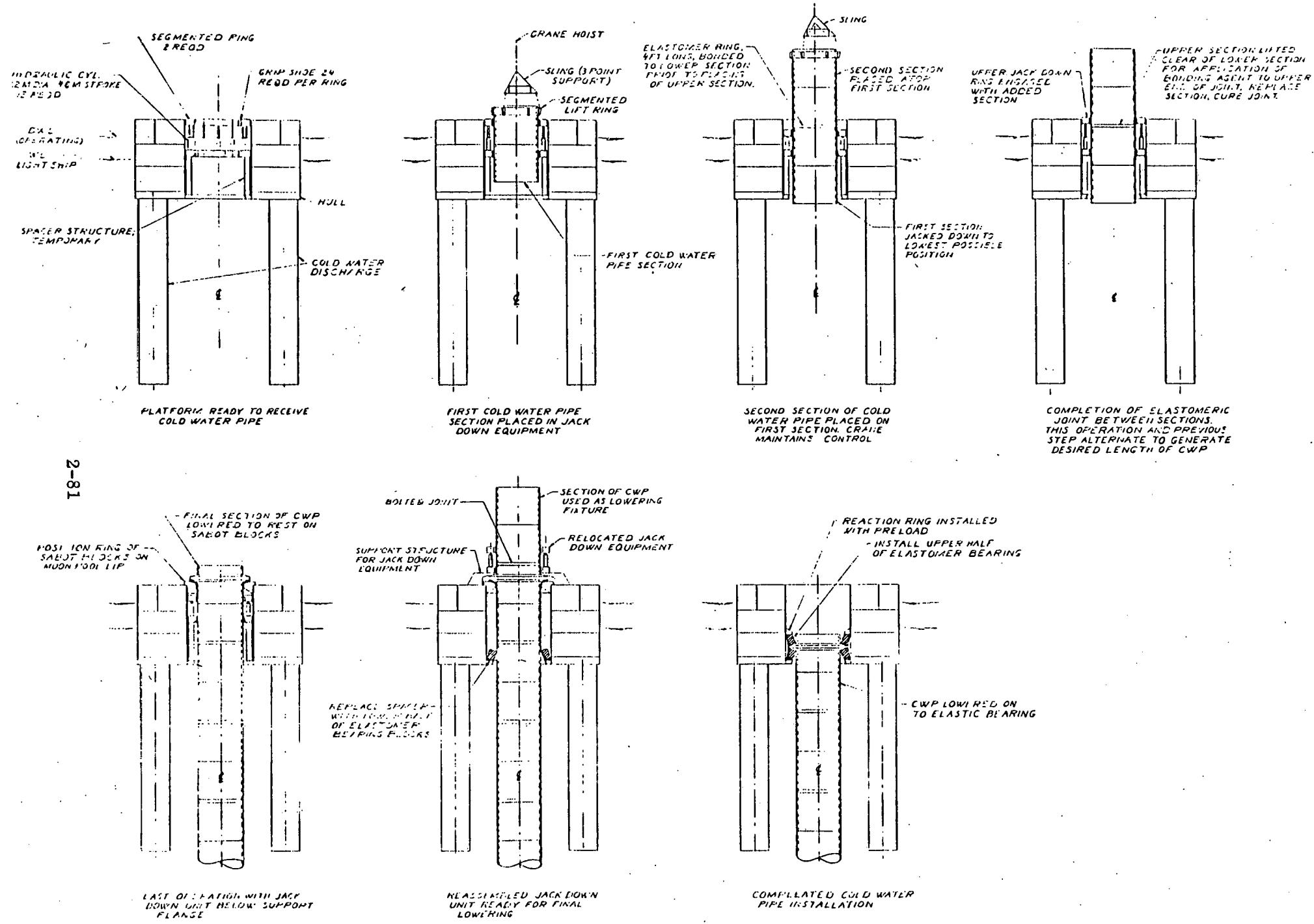
Fig. 2-25 Assembly and Installation Sequence for 100 Megawatt Cold Water Pipe
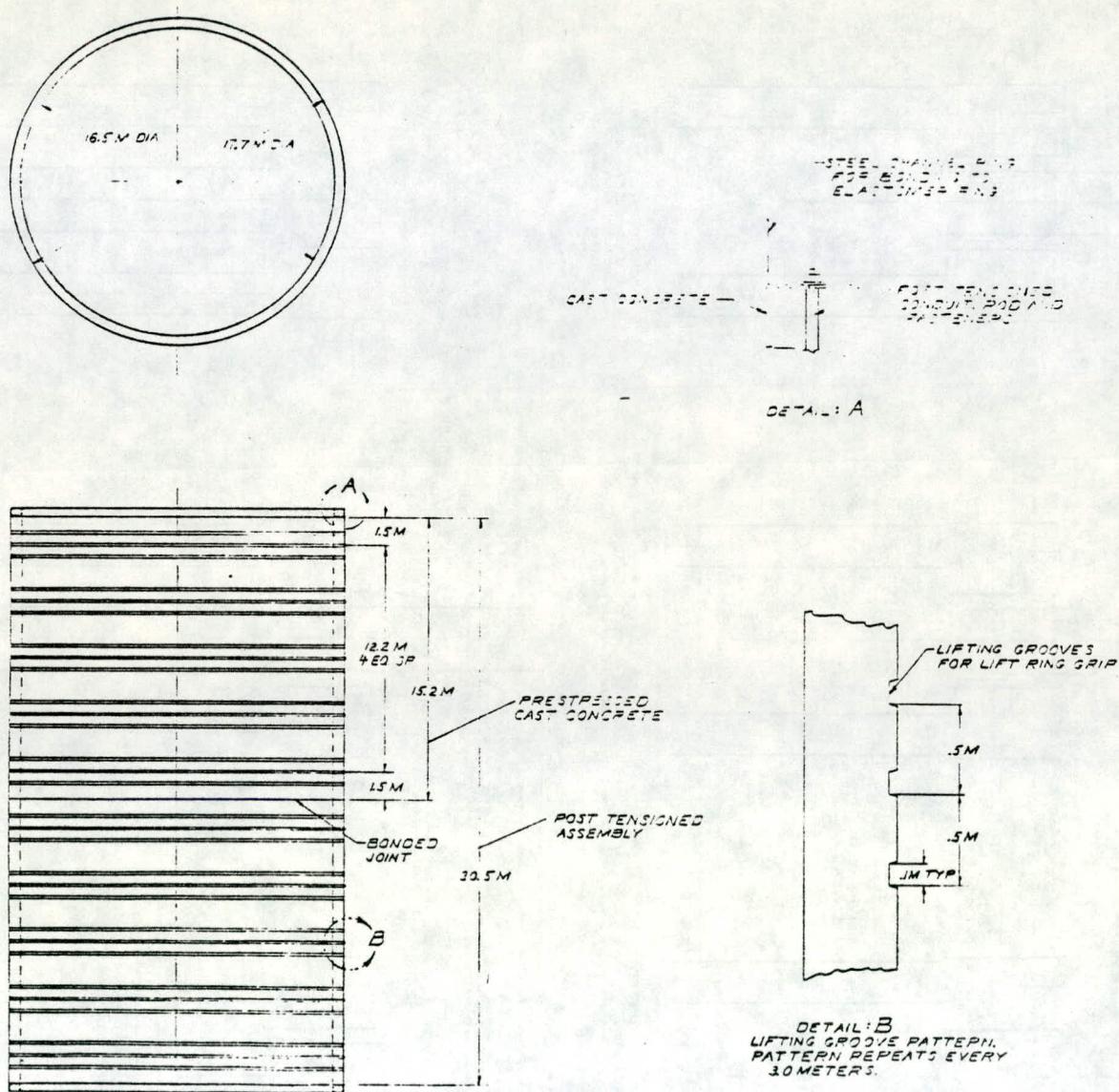
Fig. 2-26 Detail of Cold Water Pipe Section

The assembly and sequence described represents a major offshore operation. An estimate of time to complete this operation using 30m long sections is 98 days on the following basis:

Hydraulic cylinder capacity − 4 ft x 15 ft x 12 = 2262 ft^3 oil (16,919 gal.)

Complete 1/2 cycle, 16919 gal./150 gpm = 112.79 min.

Seven full cycles required/section, or 26.32 hr/section

Install section, make and cure joint − 36 hrs

Time per section − 62 hrs (2.6 days)

Total for 30 sections − 78 days

Down time − 25%

Time to completion − 98 days

Time to completion for 45m sections is 75 days. The estimated cost for CWP deployment is $23M to $28M.

Alternatives to this approach to CWP installation involve completion of CWP assembly on shore followed by towing to site, upending and floating CWP into position in the platform. The latter step may be completed by attaching the CWP to the side of the platform either structually or through a flexible hose to carry the cold seawater from a floating spar pipe separately moored or tied to the platform. The pipe may be floated into an open well between the outer hulls of a catamaran-like platform. Another option is to flood the CWP down under the surface followed by pipe positioning below the platform keel under the pipe transition, deballasting the pipe and attaching it to the bearing. In any case, these alternatives require a major ballasting system and buoyancy collar to float the 25,000 ton structure after the upending stage. A twin-hulled shape is limited to surface platforms so that for the submerged platforms structural completion at the operations site is required. The selected approach is within the state of practice in offshore technology and is considered to be the most feasible in applicability to all platforms under investigation.

A crane temporarily installed on the OTEC platform to handle the CWP segments would avoid relative motion problems between the crane barge and the jacking ring on the platform.

2.3.3.2 Sea Water Pumps. The seawater pumps are a critical element in the OTEC plant since the major parasitic power consumption is in these pumps providing the necessary water flow to the heat exchangers and primarily overcoming the flow losses in the heat exchanger. Because of the necessary size of the pumps and a desire for redundancy/serviceability multiple pumps are generally considered. LMSC has extended the analysis of Westinghouse (Ref. 3), with additional data obtained in the Test Facilities Study, and for ongoing power system development efforts. The results of this analysis differ primarily in that the economy of scale is predicted to be much less than reported by WEC.

The pump outer casing radius was determined to be well represented by $r_o = 0.316 \, Q^{1/2}$ (meters), where r_o is the outer casing radius and Q is the flow rate through the pump in m^3/s. This corresponds to a specific speed of approximately 5000. The average axial velocity through the runner is 4.54 m/s, which is a good conservative value for cavitation concerns. WEC proposed a higher velocity (8.27 m/s) for two candidate designs of pumps. These may be achievable, and may be necessary if they are to be fabricated in existing facilities which appear to be limited at about a 3 m radius. One large pump per circuit per 25 MWe net module would be pressing the fabrication limit. Multiple pumps in the circuit would require much smaller sizes (2 m) which are more readily accommodated by existing facilities.

Cost data for a series of pumps in the range of interest from the same vendor are well represented by the following:

$$\text{Cost (\$K)} = 121 \, (D)^{1.68}$$

where D is the diameter of the outer casing (= $2 \, r_o$), and 121 is an empirical fit to one representative set of date.

The trend with size, represented by the exponent on the diameter of 1.68, is a straight line fairing through the slopes of several data sets in this range of size. There is a

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small concave upward curvature to the data which is not fully reflected by the exponential fitting. However, in the range of current interest for OTEC flow rates per pump, 10 to 100 m^3/s, the trend is well represented up to about 50 m^3/s. Greater comparative costs than this trend are likely for pumps with greater than 50 m^3/s capacity.

These two functional relations result in seawater pump costs as a function of the required flow rate as follows:

$$\frac{Cost}{Q} = 55.8 \; \frac{1}{Q^{.16}}$$

This function compares with that reported by WEC (Ref. 3)

$$\frac{Cost_{(WEC)}}{Q} = 239 \; \frac{1}{Q^{.616}}$$

These two functions give the same cost for a pump capacity of approximately 25 m^3/s, while the LMSC function predicts twice the cost as predicted by WEC for 100 m^3/s. Figure 2-27 presents these cost data and the two cost models.

It is important to note that while this new LMSC cost model presents a good fit for this sizing up of pumps, the magnitude of estimates of pump costs from various vendors vary by a factor of 2-1/2 for the similar requirements. This variability emphasizes the problem of utilizing random data in developing cost trends. It is believed that the new LMSC function is a good scaling model and that it represents a potentially good price in a competitive market.

Costs have been developed for four pump capacities which in multiples total 100 m^3/s flow rate (approximately that required for one circuit of a 25 MWe net power modules). In addition to the estimated cost of purchasing the pumps the cost of volume occupied in the hull by the pumps was computed using a rate of \$662/m^3 or \$18.75/ft^3 for the

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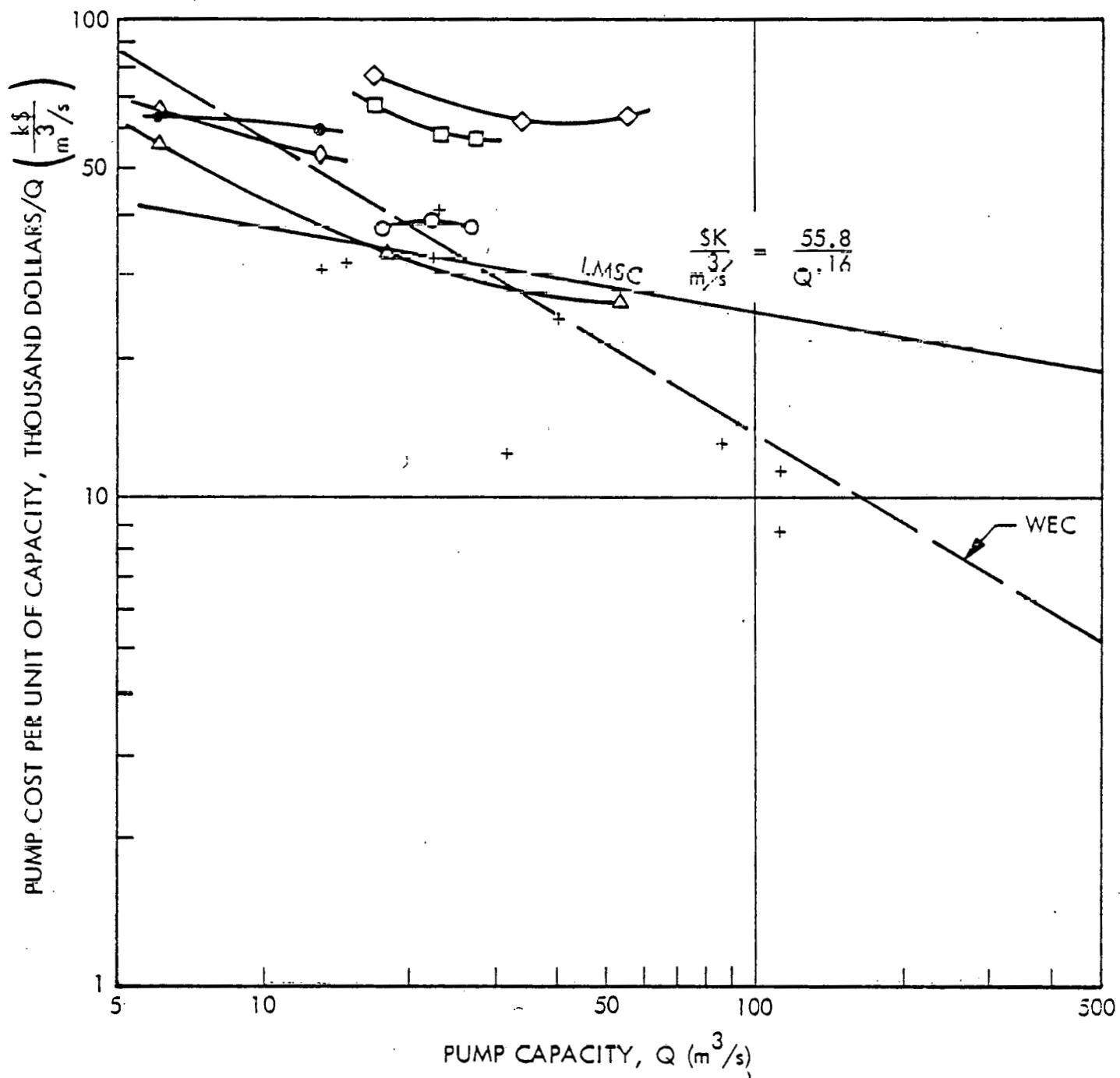
Fig. 2-27 Costs for Seawater Pumps

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value of volume in a typical hull. The total actual cost for pumps of larger capacity is less than for several smaller capacity pumps, as is evident from the cost function. The value of volume in the hull tends to reduce this economy of scale. Assuming a 1.375 packing factor for the pump assembly, the total cost is essentially independent of the rated capacity of the pumps.

The considerations for serviceability, replacement, sealoff, etc., now become the ones to dictate the number of pump units to package, since there is no clear cost advantage one way or the other (at this stage). If the pump costs are double those used in the current model, the results would tend to favor the larger (or one) pump. If the platform costs per occupied volume increase, then more smaller pumps would be indicated. If the scaling trend does rise beyond 50 m^3/s capacity, or U.S. facilities are unable to fabricate the large single pump economically, then multiple units would be indicated. At this point, there is no clear driver in the selection of the seawater pump capacity or number per module.

Covering all reasonable outcomes has resulted in the specification of a seawater pump envelope for use in all design studies and a cost of $3.5 M per circuit for the pump(s) which will be used in later design maturity. This envelope is 9 m × 9 m × 18 m with the long axis inline with the flow through the heat exchangers. In this volume the following combination of pumps can be accommodated.

1 – short ($\eta \sim 68\%$) pump rated for 25 MWe net
3 – pumps ($\eta > 76\%$) rated for 8 1/3 MWe net
or 4 – pumps ($\eta > 76\%$) rated for 6 1/4 MWe net

Note that 2 pumps of 12.5 MWe radius would be slightly wider and much less high than this envelope, and should be able to be fitted into any arrangement developed with this envelope.

The total actual cost of the seawater pumps for a 100 MWe net plant is $3.5 M × 2 × 4 = $28 M. This is on the order of 10 percent at the platform cost. It is evident that

a size, cost, producibility, efficiency optimization is needed of the pump in conjunction with the platform (arrangements, volumes, and flow losses) and the power system (flow rate requirements, head losses, enhancement). While some cost reduction is probable, the general conclusion will still stand, that the number of pumps per circuit will probably be determined by factors of redundancy, operational convenience, and serviceability. In this regard, 3 or 4 smaller rated pumps would be recommended.

2.3.3.3 Platform — Cold Water Pipe Transition. The transition structure transfers the supporting loads between the suspended cold water pipe (CWP) and the cold water pipe major foundation. Interface requirements therefore include static and dynamic load distribution, axial, torsional, and rotational bearing stiffnesses, low wear rate, 40-yr life in seawater environment, and compatability with CWP installation method. Concept options include gimbal, ball joint, heave-compensated cable, and CWP flange on clastomeric bearing. The latter approach is selected as the baseline concept and applied to all platforms.

Analysis of motions and loads for the six platforms indicates that the bending stiffness of the transition influences the extent of CWP bending stress. Results indicate that an infinite stiffness results in maximum bending and that stiffnesses of 10^9 ft lb/radian and below result in lower bending stress. The selected stiffness requirement is therefore 10^9 ft/radian. Axial stiffness of 10^7 lb/ft is selected to limit relative vertical motion between CWP and platform. Lateral bearing stiffness is chosen to be 10^4 lb/ft.

The concept depicted in Fig. 2-28 will support the CWP on the foundation with the required levels of fixity. The bearing consists of a set of 22 rubber columns, 3.5m diam., of 9.1m height above and below an annular flange fixed to the outside wall of the CWP. The foundation for these columns are extensions of the platform structure and internal to the center well. The upper foundation provides for pre-compression of the rubber columns. The dimensions shown allow for a 10-deg relative rotation between the platform and CWP. The minimum well diameter is 25m to allow for insertion of the CWP upper section with flange. Further, volume is required to allow for lateral displacement of the rubber. The bearing proportions allow for 30 percent compression. This is the maximum allowable compression for continuous flexure of 40 Shore Durometer hardness rubber (Ref. 4). With this maximum rubber compression, the required rubber column height is 9.1m. A form factor of 1.0 allows for appropriate area for rubber expansion under compression.

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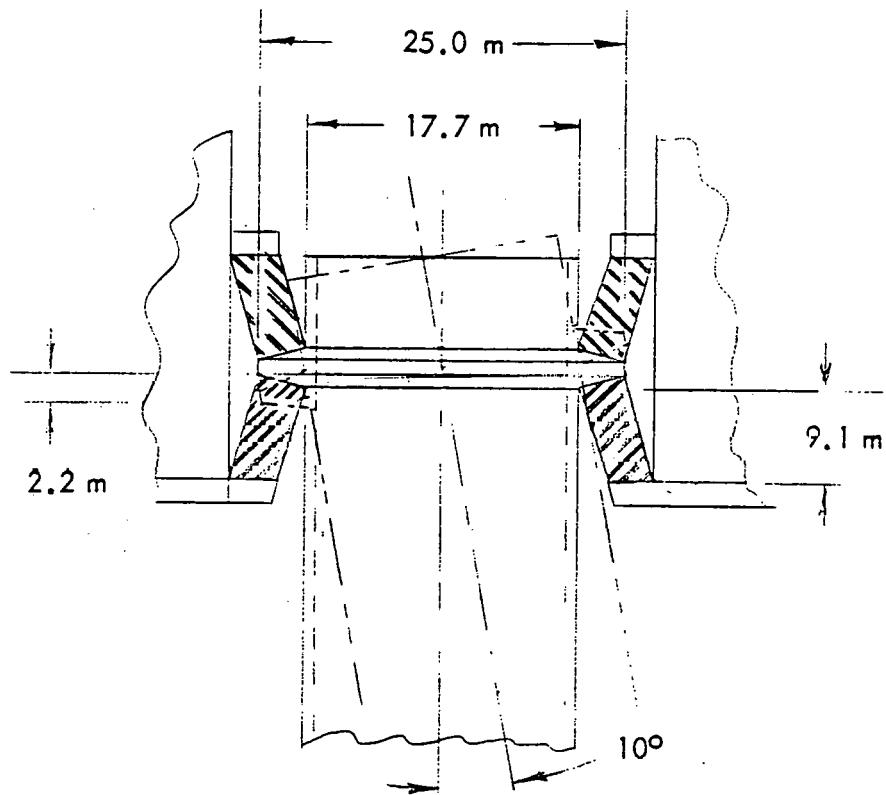
Fig. 2-28   Elastomeric Bearing for Cold Water Pipe/
Platform Interface

Angular Stiffness 3.6×10^{10} ft-lb/radian
Axial Stiffness 1.2×10^{7} lb/ft

shows that this particular design exceeds the required stiffness. Further analysis will consider a lower angular motion requirement, lower hardness rubber, and alternative bearing materials. In addition, data on the behavior of rubber in the seawater environment will be investigated.

The size of the rubber columns, the clearance with the platform, and the cost of the attachment are dependent upon the actual platform configuration, the environmental conditions for the site, and the design considerations of the cold water pipe. This baseline design concept indicates capability to satisfy all these requirements within a nominal space and for a nominal weight. The baseline transition section is used throughout this phase with refinements anticipated in conceptual design.

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2.3.3.4 <u>Water Ducts.</u> The baseline power system specified for this study included warm and cold water circulating piping as shown in the following table:

Module Output MWe (gross)	Outside Diameter of Pipe (feet)	For a total 25 MWe (combined modules)			
		No of Modules	Length of Piping (feet)	Dry Weight of Piping (short tons)	Cost of Piping ($M)
25	25	1	600	1,800	1.77
12.5	18	2	1,200	1,500	1.45
8	15	3	1,800	1,300	1.80
5	12	5	3,000	1,800	1.83

These pipe diameters were used in the comparison design of the six platforms. The length of the circulating piping was minimized in each platform design to be consistent with the design guidelines. The length of piping is considered only as that length which is within the hull boundary. The cold water discharge extensions utilized by the surface platforms to provide discharge below 100 meters is not included as internal piping.

The average lengths of internal ducting for the six 100 MWe net platform designs discussed in Section 2.4 are generally less than that specified above. These duct lengths are not flow lengths, since components having seawater (heat exchangers, pumps) are not included. Duct lengths for 100 MW(e) platforms are shown in Table 2-27.

Three platforms have significantly shorter lengths of total ducting than the others (spar, circular barge, and submersible). The semi and the ship have complex flow paths for distributing the cold water requiring up to 6.7 times the duct length required by the submersible. The most satisfactory duct length would be the most cost effective. For the same duct diameter the shortest length duct would be the best cost solution for a duct alone. The dual purpose duct/wing tank arrangement for the ship requires consideration of the overall cost of the duct and hull system. The comparison of platforms for the specified internally-mounted power system used these arrangements and ducting lengths and diameters as the most consistent basis for comparison.

Table 2-27

INTERNAL LENGTH OF SEAWATER DUCTING FOR 100-MW(e) NET PLANT

TYPE OF PLATFORM	COLD WATER		WARM WATER		TOTAL		ℓ/ℓ_{SPAR}
	M	(FT)	M	(FT)	M	(FT)	
SHIP	147	(481)	25	(83)	172	(564)	2.26
CIRCULAR BARGE	38	(125)	48	(158)	86	(283)	1.13
SEMISUBMERSIBLE	155	(510)	41	(135)	196	(645)	2.58
TUNED SPHERE	101	(332)	39	(128)	140	(460)	1.84
SUBMERSIBLE	23	(75)	70	(229)	93	(304)	1.22
SPAR	29	(94)	47	(154)	76	(248)	1.0

Optimization of the seawater ducting design must account for several very critical features of the seawater system and interfaces with the hull, seawater pumps, and the power system. The importance of optimizing the seawater ducting is shown by the cost of the system. The total cost of seawater ducting consists of at least the following elements:

1. Cost of material for the duct
2. Cost of erecting the duct in the hull
3. Cost of a foundation to support the duct and the water contained in the duct and to distribute the load into the hull structure. The foundation may be estimated to weigh 10 percent of the supported weight.
4. Cost of biofouling/corrosion control.
5. In addition to these costs, the duct occupies a volume in the hull which could be used for other purposes. Hence a volume cost evaluation must be added in deriving the effective cost of duct. This volume cost should be based on the cost per unit volume for the hull and position control system. This rate varies between $500/m^3$ and $700/m^3$ for the 100-MWe net platforms described in Section 2.4.

An estimate of these cost elements per unit length of ducting is in Table 2-28.

The effective value of the sea water ducting in the comparative platform designs for 100 MWe net is presented in Table 2-29.

The large cost values for the seawater ducting are evident as it is as much as 48 percent of the total platform cost for the ship and 46 percent for the submersible. The smallest cost percentage is for the spar with 19 percent of the platform cost devoted to the duct system. As a result of these large duct costs, it is apparent that this is an area for cost refinement, if not major reduction. As one avenue to provide cost reduction, the costs of the ducting has been developed as a function of inside diameter of the duct. The premise is that a smaller diameter duct would have lower actual costs (material, erection, and foundation) and lower costs for use of volume. The cost of additional power to pump the water at higher velocities in the smaller diameter duct must then be weighed against the savings in the cost of the duct.

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Table 2-28
UNIT COST OF SEAWATER DUCTING

1. MATERIAL ⎫	$3100/TONNE (STEEL) =	$30,512/M	($9300/FT)
2. ERECTION ⎭			
3. FOUNDATION		$15,194/M	($4631/FT)
4. CORROSION		SMALL	
	TOTAL ACTUAL COST =	$45,706/M	($14,931/FT)
5. VOLUME COST @ $500/M^3	=	$22,772/M	($6941/FT)
@ $700/M^3	=	$31,877/M	($9716/FT)
TOTAL EFFECTIVE COST OF DUCTING		$68,478/M	($21,872/FT)
PER UNIT LENGTH		$77,583/M	($24,647/FT)

Table 2-29
COMPARATIVE COST VALUE OF SEAWATER DUCTS FOR 100-MW(e) NET

100 MWe NET	EFFECTIVE COST VALUE OF SEA WATER DUCTING	PERCENT OF PLATFORM COSTS
SHIP	$ 94M	48
CIRCULAR BARGE	47	25
SEMISUBMERSIBLE	107	46
TUNED SPHERE	77	34
SUBMERSIBLE	51	27
SPAR	42	19

The results of this evaluation of duct diameter indicate that a duct nominally sized for 7 fps water velocity is 2.73 times as costly as the optimum sized duct (Fig. 2-29). The nominal 7.6 m (25 ft) diameter duct becomes optimal at 4.4 m (14.5 ft) with a resultant velocity of 20 fps. A system designed for such high velocities will require great care to avoid large flow losses as the flow turns, diffuses into the heat exchangers and is diffused into the sea. Hence, a total flow system optimization is required, including power system performance (and even optimization), to assure that the least cost duct system is designed. It is conceivable to realize a 50 percent improvement in the cost of the internal duct systems.

There are several features which suggest further savings could be realized by placement of the duct exterior to the hull or as a part of the side of the hull. This latter approach has been employed in the design of the ship configuration, Section 2.4.1. It seems unecessary to have a platform which has a double hull (for collision safety) and carries a pipe inside which is full of water. This requires three (3) barriers to be built having room pressure to hydrostatic pressure as a design requirement between the barriers. If the seawater ducts were placed exterior to the hull there would need to be only one (1) barrier and that one would have a design differential pressure which is very small (accounting only for density gradients, pumping head, and oscillatory pressure loads). The foundation structure would probably cost as much as for the internally-mounted duct. There might be a need to insulate the cold water portions of an external duct, but this might be less costly than the insulation/air conditioning for the internally mounted ducts. The external duct could be part of the hull structure and could thereby provide some collision protection. The resultant platform would be smaller by at least the volume of the extracted ducts resulting in a small structural cost for the hull.

These considerations could be expected to provide some additional refinement and reduction in the cost of the seawater duct system. Overall integrated platforms reflecting these concepts are expected to be not much changed in comparison with each other. They will all have the same potential for some improvement. The seawater duct diameter specified in the baseline power system appears to be an adequate
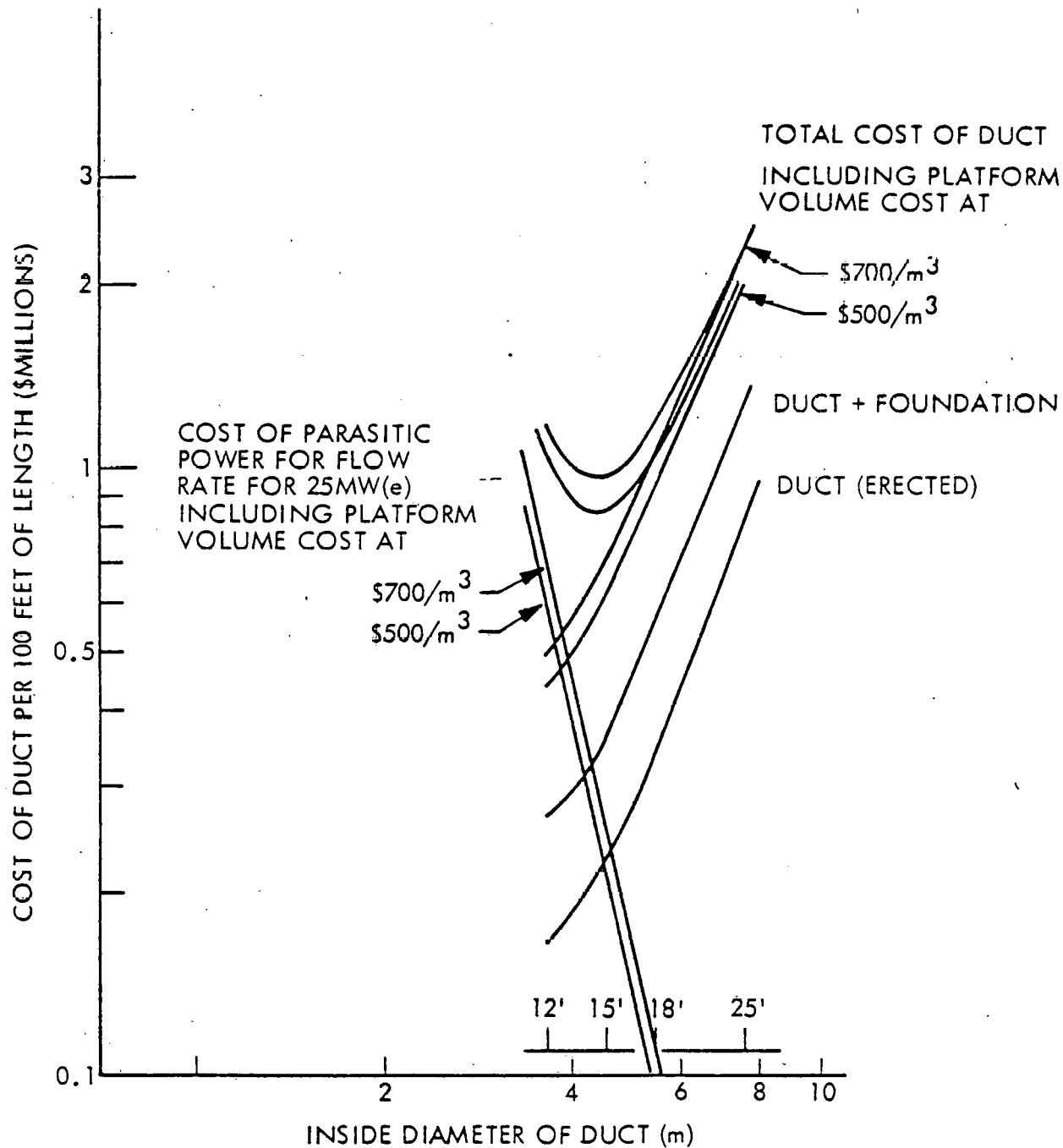
Fig. 2-29 Cost of Seawater Ducts

indicator of the arrangements and first order costs for the integrated OTEC plants developed for comparison of hull types. Some cost reductions could be anticipated in this subsystem during conceptual design.

The following Section, 2.3.3.5, discusses the materials compatibility problems between upstream components, such as the seawater ducting, and the heat exchanger materials. There appear to be several material and protection systems that will meet the needs of most candidate heat exchanger materials. This is an area which requires continuing coordination and optimization with the power system.

2.3.3.5 <u>Biofouling/Corrosion Control</u>. Biofouling and corrosion control methods must consider the entire seawater system. These considerations include materials galvanic compatibility, reliability and life of coatings and cathodic protection systems, and maintenance costs for each system. An example of galvanic incompatibility would be a steel cold water pipe and steel ducting with an aluminum heat exchanger. A potential solution to this combination of materials is a high quality paint coating system and cathodic protection or cathodic protection alone to prevent corrosion of the steel.

The experience with coatings and cathodic protection systems used on offshore platforms has demonstrated that there are corrosion protection coatings that will survive more than 10-yrs with only minor maintenance. The cathodic protection system experience indicates 20-yr life systems can be readily achieved. A similar problem of galvanic incompatibility would occur if a copper-nickel alloy were used for upstream screens if the heat exchangers were aluminum. Table 2-30 provides a listing of candidate systems materials and their compatibility or incompatibility. The application of biofouling control measures should consider the entire seawater system. An example is that should no biofouling control measures be applied to the platform it would act as a large breeding area for biofouling that would continuously release micro-organisms into the seawater flow into the heat exchangers. The result would be a high cost of maintaining clean heat exchangers. The use of anti-fouling paints on the platform and cold water pipe must also consider the heat exchanger materials. Those anti-foulant coatings that use cuprous oxide as a toxic agent increase the pitting attack on aluminum and on steel alloys that are downstream.

Table 2-30

HEAT EXCHANGER/PLATFORM MATERIALS COMPATIBILITY

	HEAT EXCHANGER MATERIALS			
PLATFORM MATERIALS	ALUMINUM ALLOYS	Al-6X SST	C.P. Ti	Cu-Ni 90-10
CW PIPE				
STEEL	NC	C	C	C
ALUMINUM	C	C	C	C
CONCRETE	C	C	C	C
GRP/PLASTIC/RUBBER	C	C	C	C
DUCTING				
STEEL	NC	NC	NC	NC
ALUMINUM	C	NC	NC	NC
GRP/PLASTIC	C	C	C	C
CONCRETE	C	C	C	C
SST	C	C	C	C
SCREENS				
Cu-Ni (90-10)	NC	C	C	C
STEEL-GALVANIZED	C	C	C	C
STEEL-COATED W/A.F.	C	C	C	C
SST	C	C	C	C
CW PIPE TRANSITION				
STEEL	NC	C	C	C
ALUMINUM	C	C	C	C
BRONZE	NC	C	C	C
GRAPHITE	C(?)	C	C	C
PUMPS				
STEEL	NC	C	C	C
SST	C	C	C	C
BRONZE	NC	C	C	C
Ni CAST IRON	NC	C	C	C

NC = NOT COMPATIBLE

There are several systems which can be used in combination to provide both biofouling control and corrosion protection. These are long life antifouling coatings, such as "No Foul", impregnation of anti-foulants in concrete mix, mechanical cleaners, and sonic vibrations. These systems all involve reasonably large costs. The risks in their use are mainly because of the short experience that has been obtained with them and with possible degradation of mechanical properties.

A recommended platform material selection and corrosion and biofouling control measures for those materials are as follows. The hull structural material should be concrete with galvanized re-bar, cathodic protection, and anti-foulants should be impregnated in the concrete. Galvanized re-bar in combination with cathodic protection can assure 40 year life. Anti-foulants impregnated in concrete have demonstrated "hard" fouling control for more than 7 yrs (total experience to date). These recommendations lead to a minimum life cost of less than $100K for the cathodic protection system for the concrete and approximately $350K for the biofouling control for a 10-yr period with the spar platform.

The spar configuration should have the least cost for biofouling control since the major hull surface is located at greater depth than for other configurations where the growth of biofouling is known to be significantly reduced.

2.3.3.5 <u>References</u>.

1. Department of Energy, <u>OTEC Demonstration Plant Environmental Package</u>, 14 Jul 1977

2. Westinghouse Electric Company, <u>Ocean Thermal Power Plants Cold Water Pipe, Seawater Pumps, and Platform Station Keeping</u>, by T. Little and H. Davison, 27 Sep 1977

3. -----, <u>Deep Water Pipe, Pump and Mooring Study, Ocean Thermal Energy Conversion Program</u>, by J. E. Little, J. D. Marks, and K. H. Wellman, Annapolis Report No. COO-2642-3, Jun 1976

4. <u>Military Handbook 149A</u>, 30 Jun 1965, pp. 22-31

2.3.4 Position-Control System

Position control is required at all sites, with grazing of a production plant at the Brazil site. The two principal options are mooring and dynamic positioning. System requirements include:

(1) Orient platform to minimize aero-hydro drag, recirculation of seawater, and platform seaway response.

(2) Mooring effective from 955 m at Keahole Pt. to 5455 m at Brazil site.

(3) Allowable line load is 20% of breaking strength for operation and 50% for extreme conditions.

(4) Assume wind, current, and wave drag are colinear and normal to maximum projected platform area.

(5) Watch circle to be 5% of water depth with electrical transmission.

(6) Various seafloor conditions — terrigeneous and clayey silt at Gulf of Mexico site, for example.

(7) Variable thrust and vectoring for dynamic positioning system, if required.

This section begins with an analysis of the horizontal loads on the platform to establish the holding power required for position-keeping in the extreme condition. This condition consists of 100-yr storm wind, wave, and current acting in the same heading normal to the platform maximum projected area. Hence, it is assumed that the azimuthing control capability is not operational in this condition. Following this is a treatment of the mooring system and dynamic positioning system, including cost comparisons for the combinations of platform type (6), operational site (5) and net plant output (50 to 500 MW(e)).

2.3.4.1 Environmental Loads.

The horizontal force on the plant in the extreme conditions is obtained as

$$F_T = \frac{1}{2} \rho \, A V_s^2 \, C_D + \frac{1}{2} \rho_a \, A_w \, V_w^2 \, C_{Dw} + F_{CWP} \, (V_s, D_T, T_T)$$

$$+ F_{WAVE} + F_{LINE} \, (V_s, D, L) + F_{DISCH} \, (N, V_s, L, D)$$

where

A	=	submerged projected area of platform
A_w	=	above waterline projected area
C_D	=	platform current drag coefficient
C_{DW}	=	wind drag coefficient
V_s	=	surface current, extreme
$\overline{V}_0$	=	surface current, annual average
V_w	=	wind speed, extreme
$\overline{V}_w$	=	wind speed, annual average
F_{DISCH}	=	discharge pipe drag
F_{CWP}	=	cold water intake pipe drag
F_{LINES}	=	mooring line drag
ρ	=	water density
ρ_a	=	air density

Data on site conditions listed in Table 2-31 indicate the extreme case (100-yr storm), operational current, and assumed annual average wind speed. The latter two are criteria for determining annual fuel requirements for thrusters. The extreme current profile is given in Fig. 2-30. Areas and drag coefficients for each platform type are shown in Table 2-32. These coefficients, comparable to those reported in Ref. 1, are based on the submerged shape of each 100-MW(e) (net) platform design. Since the platform proportions do not vary significantly for the 200 and 500 MW(e) (net) designs, it is assumed that the coefficients are independent of platform size. The mooring line drag and seawater discharge pipe drag were neglected in the analysis as these components are less significant than platform and cold water pipe (CWP) drag.

The dependence of CWP drag on Reynolds number is included in the typical results shown in Table 2-33. The dependence of drag on surface current and pipe diameter is illustrated in Fig. 2-31, while the significant dependence of drag on CWP upper end depth is shown in Fig. 2-32. The following expression for CWP drag in the extreme current profile is based on these results.

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Table 2-31
SITE ENVIRONMENTAL CHARACTERISTICS

Criteria	Parameter	Hawaii	New Orleans	Brazil	Puerto Rico	Key West
100-Yr Storm	Max Wind (kts)	65.7	100.3	61	92.8	113.8
	Gust (kts)	95.2	145.4		134.6	165.0
	$H_{1/3}$(ft)	35.9	58.1	29.0	44.2	45.8
	$T_{1/3}$(sec)	12.72	15.91	18.0	13.8	13.67
	Current (kts)	2.18	2.49	3.2	2.76	6.4
Typical	Wind, kts	20-44	20-56	20-40	20-40	20-56
	Annual Average Wind (kts)	5	5	5	5	5
	$H_{1/3}$(ft)	20	20	20	20	20
	T_0(Sec)	10.3	10.3	10.3	10.3	10.3
	Current (kts)	1.13	1.17	0.5	1.21	4.73
	Depth	3,150	3,950	18,000	4,000	4,850
	Depth at 30°FΔT	1,089-1,419	891-2,442	1,155	1,568-2,045	1,353-2,145
	Depth at 36°FΔT	1,568-3,300	1,320-4,125 (7 mos)	1,188-2,013	2,079-2,805	1,881-4,125

Table 2-32
OTEC PLATFORM CHARACTERISTICS

PLATFORM	NET OUTPUT [(MW(e)]	MAX BEAM (m)	LENGTH (m)	DRAFT (m)	CURRENT FRONTAL AREA (m²)	CURRENT LATERAL AREA (m²)	CURRENT DRAG COEFF (C_D)	WIND FRONTAL AREA (m²)	WIND LATERAL AREA (m²)	WIND DRAG COEFF (W_D)	DEPTH OF CWP ATTACH. (m)
SHIP	100	66	165	25	1,650	4,125	0.5	462	1,155	0.6	25
	200	82	305	25	2,050	7,625	0.5	574	2,135	0.6	25
	500	82	356	42	3,444	14,952	0.5	1,476	6,408	0.6	42
BARGE	100	98	98	31	3,038	3,038	0.7	1,194	1,194	0.6	31
	200	105	105	38	3,990	3,990	0.7	1,260	1,260	0.6	38
	500	149	149	61	9,089	9,089	0.7	6,556	6,556	0.6	61
SPHERE	100	91	91	73	5,682	5,682	0.6	1,862	1,862	1.0	73
	200	115	115	92	9,387	9,387	0.6	2,625	2,625	1.0	92
	500	175	175	140	20,649	20,649	0.6	4,163	4,163	1.0	140
SEMI-SUBMERSIBLE	100	120	132	40	3,200	3,700	0.6	1,000	1,325	1.0	40
	200	142	144	48	4,776	5,352	0.6	1,120	1,848	1.0	40
	500	162	216	80	10,336	11,872	0.6	1,600	2,600	1.0	80
SUBMERSIBLE	100	49	116	69	2,351	6,150	0.5	347	347	1.0	49
	200	49	195	69	1,886	9,555	0.5	347	347	1.0	69
	500	119	335	69	11,122	16,415	0.5	1,000	1,000	1.0	69
SPAR	100	100	100	115	5,900	5,900	0.7	750	750	1.0	120
	200	118	118	121	8,117	8,117	0.7	920	920	1.0	121
	500	156	156	153	16,218	16,218	0.7	1,320	1,320	1.0	133

2-103

Fig. 2-30 Normal for Key West and Extreme-Current Profile for all Sites (Ref. 6)

2-104

Table 2-33

COLD WATER PIPE HYDRODYNAMICS

```
SURFACE CURRENT;KNOTS 1
NUMBER OF PIPE SEGMENTS1
PIPE OUTSIDE DIAMETER(FT.) 50
PIPE INSIDE DIAMETER(FT.) 54
PIPE DENSITY(LB/FT3) 150
PIPE LENGTHS(FT.) 3218
MEAN FOULING  THICKNESS(FT.) 0
DEPTH OF EXTERIOR FOULING(FT.)  0
DEPTH OF UPPER PIPE END00
STANDARD OR EXTREME CURRENT PROFILE?(1 OR 2)2
VOID PERCENTAGE IN WALL 25
```

COLD WATER PIPE HYDRODYNAMICS

```
TOTAL PIPE LENGTH;FT.   3218.00
TOTAL PIPE WEIGHT;LBS.(AIR)        127381421.00
                     (WATER)        54915546.10
```

DEPTH FT.	CURRENT FT/SEC	REYNOLDS NUMBER	CD	CL	DRAG LBS.	SUMD LBS.	STROUHAL NUMBER	SHEDDING FREQ.;HZ
163.45	1.35	.77E+07	.44	0.00	9795.	9795.	.30	.0030
324.35	1.26	.68E+07	.44	0.00	7515.	17310.	.30	.0070
485.25	1.16	.58E+07	.44	0.00	5494.	22804.	.30	.0060
646.15	.97	.48E+07	.44	0.00	3830.	26634.	.20	.0004
807.05	.81	.40E+07	.42	0.00	2571.	29205.	.20	.0028
967.95	.67	.34E+07	.40	0.00	1700.	30905.	.20	.0023
1128.85	.57	.28E+07	.38	0.00	1144.	32050.	.20	.0020
1289.75	.49	.24E+07	.36	0.00	811.	32861.	.20	.0017
1450.65	.44	.22E+07	.35	0.00	620.	33481.	.20	.0015
1611.55	.41	.20E+07	.33	0.00	513.	33995.	.20	.0014
1772.45	.39	.19E+07	.33	0.00	450.	34445.	.20	.0013
1933.35	.37	.18E+07	.32	0.00	404.	34849.	.20	.0013
2094.25	.35	.17E+07	.31	0.00	356.	35206.	.20	.0012
2255.15	.33	.16E+07	.30	0.00	297.	35502.	.20	.0011
2416.05	.29	.14E+07	.29	0.00	225.	35727.	.20	.0010
2576.95	.25	.12E+07	.27	0.00	151.	35878.	.20	.0009
2737.85	.20	.99E+06	.24	0.00	89.	35967.	.20	.0007
2898.75	.16	.78E+06	.22	0.00	49.	36015.	.20	.0005
3059.65	.13	.66E+06	.20	0.00	33.	36048.	.20	.0005
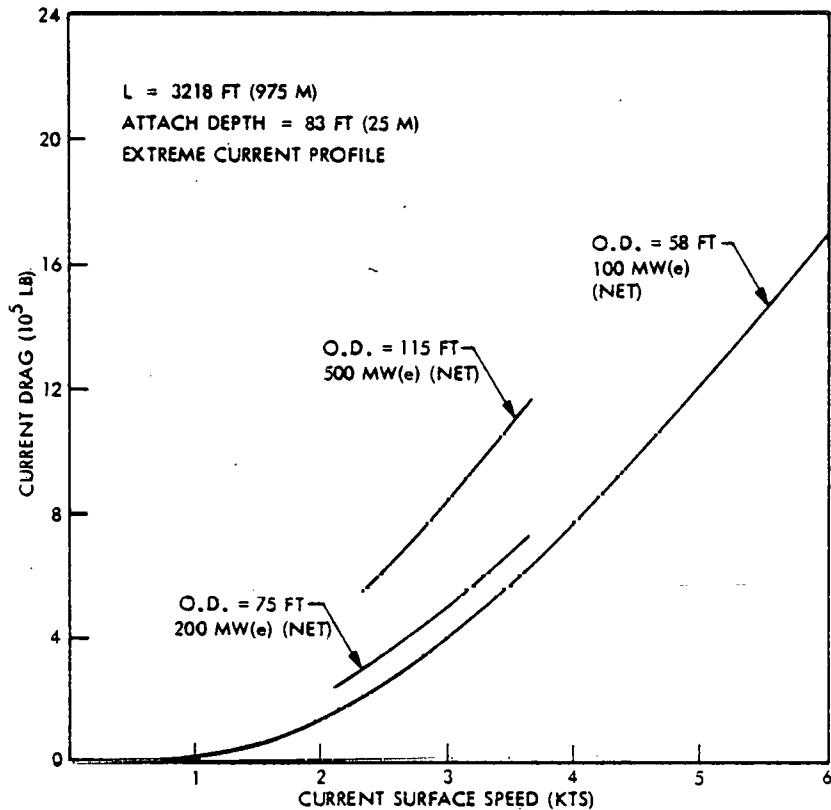
Fig. 2-31   Cold Water Pipe Current Drag vs. Current Surface Speed
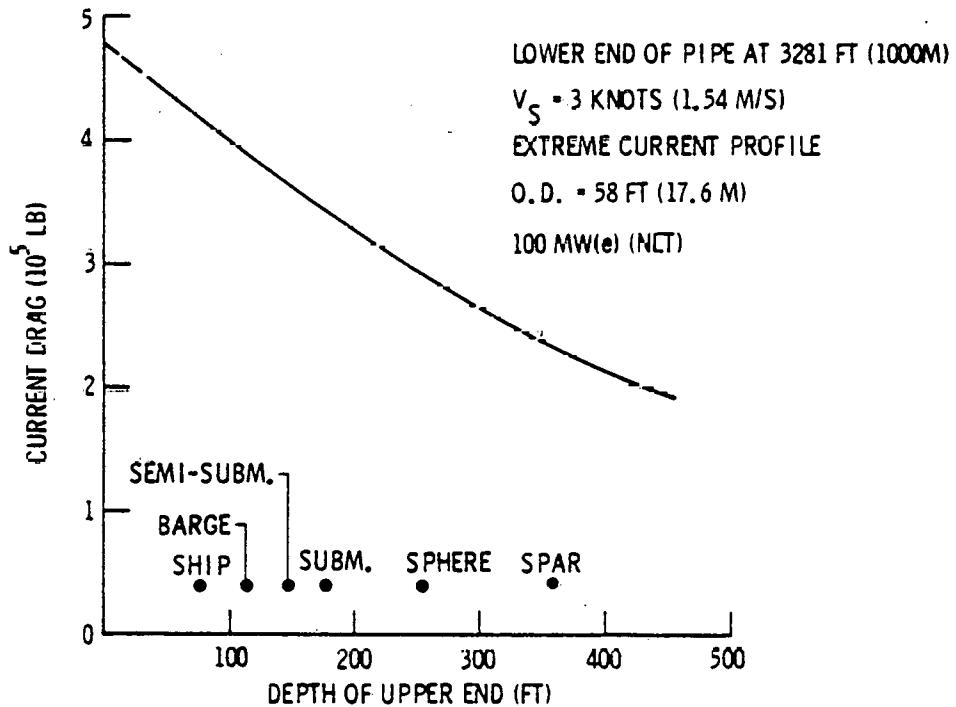
Fig. 2-32 Cold Water Pipe Current Drag vs. Depth of Attachment

2-106

$$F_{CWP} = \frac{1}{2} \rho \, \overline{C}_D \, V_s^2 \, dL - K \left(\frac{V_s}{5} \right)^2 \left(Z_A - Z_o \right)$$

where

$\overline{C}_D$ = equivalent drag coefficient, 0.091

d = CWP OD

L = CWP length

Z_A = depth of CWP upper end, ft

Z_o = 83 ft

K = $\dfrac{dF}{dZ_A}$, 667 lb/ft

The seaway induces a slow drift oscillatory force on the moored platform. An estimate of this force is based on the theory of Maruo as verified by Remery and Hermans (Ref. 3).

$$F_{WAVE} = \frac{1}{2} \rho g \, (Ra)^2 \, L$$

where

g = acceleration of gravity

R = wave reflection coefficient

a = rms wave amplitude $\left(= \dfrac{1}{3} H_{1/3} \right)$

L = platform length

The variation of platform size with net power output in the determination of platform drag is treated by scaling platform length and area as follows,

$$\left(\frac{L_1}{L_2} \right) = \left(\frac{P_1}{P_2} \right)^{0.33} \quad , \quad \left(\frac{A_1}{A_2} \right) = \left(\frac{P_1}{P_2} \right)^{0.67}$$

2-107

where P is the net plant output. These scaling factors are good first approximations to the design data given in Table 2-32.

A sample of results obtained for six platform types at five sites is shown in Figs. 2-33 through 2-35. For the extreme condition (100-yr storm, colinear drag components, and unfavorable heading) the first figure illustrates the relative cumulative contribution of wind, wave, and current for the ship in the Key West site. The range of proportions in this case varies with platform size as follows:

Drag Component	Percent of Total Drag	
	100 MW(e) NET	500 MW(e) NET
Platform Current	42	57
Platform Wind	6	11
Platform Wave	32	20
CWP Current	20	12

These proportions vary with platform type depending on frontal area relative to the ship. The variation of ship total drag with site (Fig. 2-34) clearly indicates that Hawaii produces the lowest and Key West the highest drag, higher by a factor of five. Total drag force for the 100 MW-(e) (net) platform increases from 1.2×10^6 lb in Hawaii to 6×10^6 in Key West. This conclusion applies to the other platforms as well, although the factor is dependent on platform type.

Total drag for platform in the Gulf of Mexico and high current Key West sites increases with operating displacement (Fig. 2-35). The spar has the lowest and the semi-submersible the highest drag in the Gulf, while in Key West the spar drag exceeds the drag of the semi-submersible. Drag of the other three platforms is within the drag of these platforms.

2.3.4.2 Mooring System. The mooring system consists of multipoint spread mooring lines attached to the platform and to deadweight anchors on the seafloor. High strength chain at the anchor attachment prevents line wear due to chafing. Tensioning winches mounted on the platform provide line length and tension control for platform azimuthing
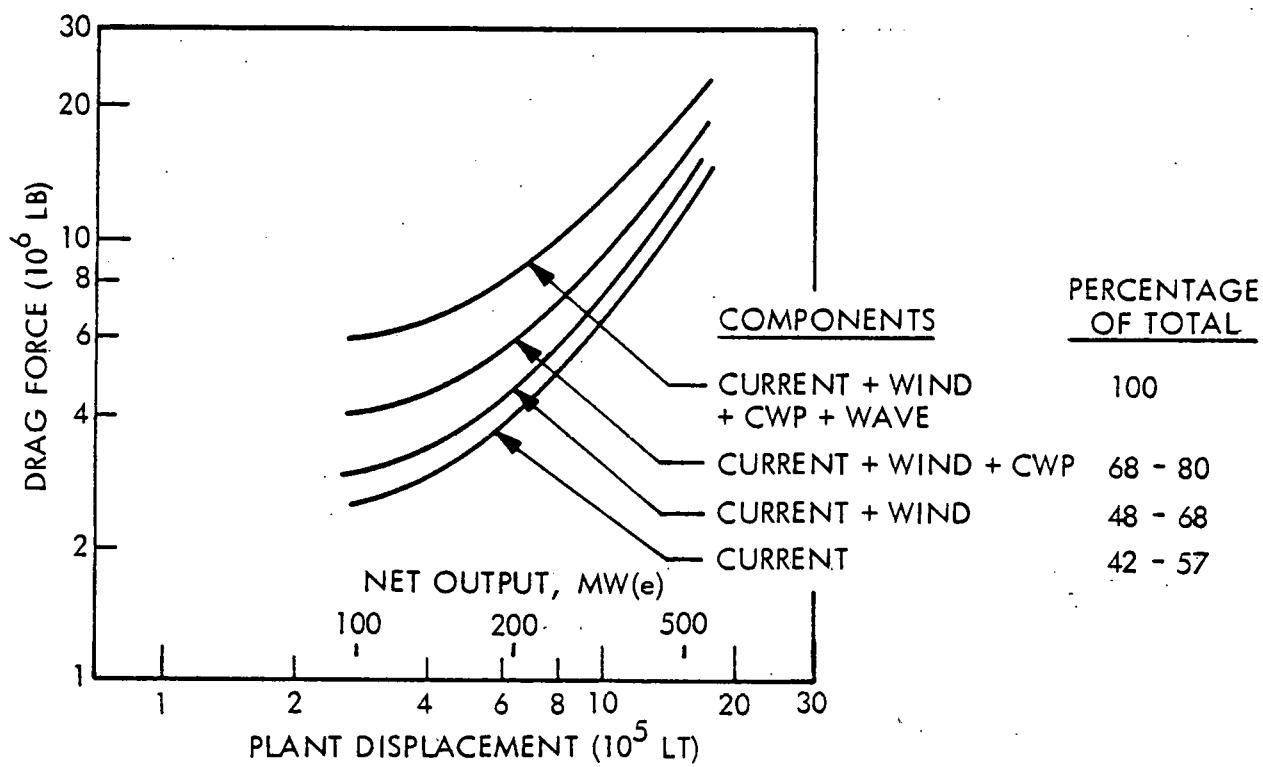
Fig. 2-33   Ship Drag vs. Size at Key West Extreme Conditions
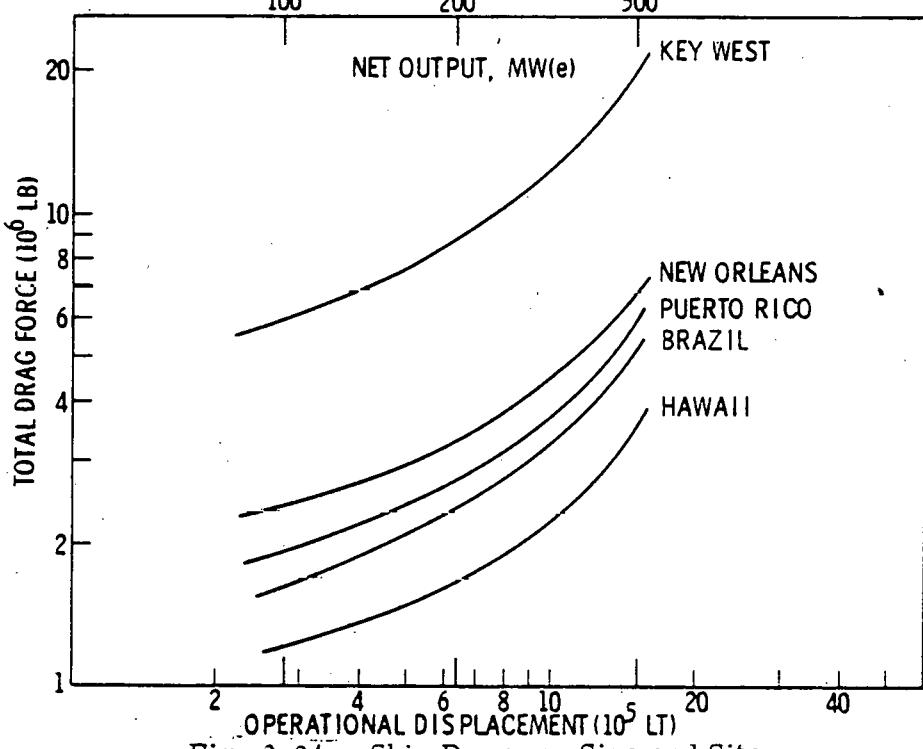
Fig. 2-34   Ship Drag vs. Size and Site

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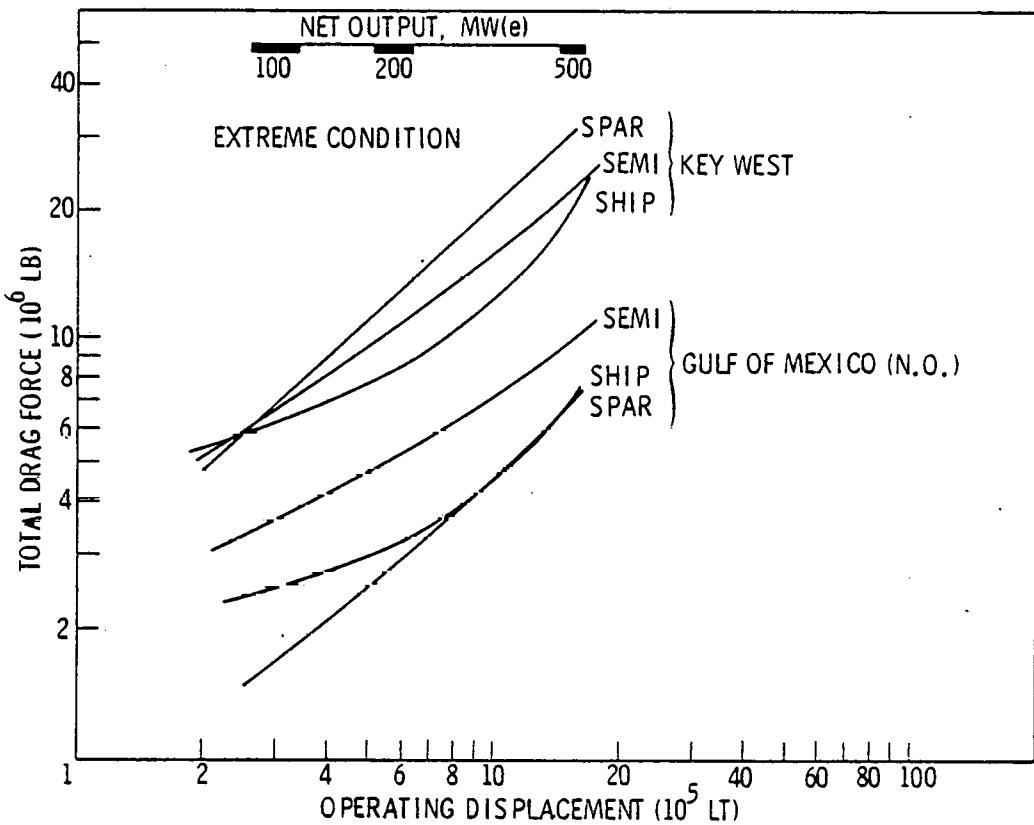
Fig. 2-35 Platform Drag vs. Platform Size, Type, and Site

and positioning in changing environmental conditions.

The concrete deadweight anchor is selected, based on its "simplicity, reliability, and holding capacity" (Ref. 4). Alternatives include free-fall concrete deadweight, pile, plate, and drag embedment anchors. The strongest commercially available line, 10-in.-diam. nylon braid, has a breaking strength of 2.1×10^6 lb. Anchor chain is high strength size four with a breaking strength of 1.9×10^6 lb. Deployment of the mooring system consists of floating each anchor to site, ballasting, and lowering the anchor on the mooring line with the assistance of a crane barge and tugs.

A functional model for the mooring system provides a method of establishing a set of parametric cost data for the various platforms and sites. In addition, a baseline design mooring system is analyzed to demonstrate the technical feasibility of this approach to position-keeping.

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The cost functional model is summarized in Table 2-34. The anchor function is based on two concrete deadweight anchor designs for deep ocean and high current sites (Ref. 4). The costs are based on engineering estimates or quotations and include forty percent for contingency, engineering, and profit. Replacement costs for the mooring lines only are included in these results.

Table 2-34

SUMMARY OF MOORING SYSTEM FUNCTIONAL MODEL

Component	Unit Cost	Cost Function
1. Line 10 in. 2.1×10^6 lb 26.5 lb/ft Specific gravity 1.14	$142/ft	$142.3 \times N_L \times L_L \times N_{LL}$
2. Present Worth Factor for 6 Replacements & Original	–	$2.6 \times N_L \times L_L \times N_{LL}$
3. Chain (Size 4)	$91.7/ft	$91.7 \times N_L \times 200 \times N_{LL}$
4. Anchor (Concrete Deadweight)	$293/LT	$293 (8790 + 3.31 F_H) \times N_L$
5. Traction Winch	–	$1553 \times T \times N_L$

L_L = line length, ft

N_L = number of legs, 3

N_{LL} = number of lines per leg, $= T \times 10^{-6}$ lb

F_H = total platform drag, LT

T = line tension, $= 1.6 F_H$, LT

Deployment costs, less than two percent of the total mooring system cost, are excluded from this summary. System costs shown in Fig. 2-36 vary between $32 M and $120 M for a 100-MW(e) (net) platform and between $100 M and $320 M for a 500-MW(e) (net) platform. The lowest cost mooring system is that for the submersible in Hawaii (not shown). These results generally follow the total drag data variation between size, site, and platform type.

2-111
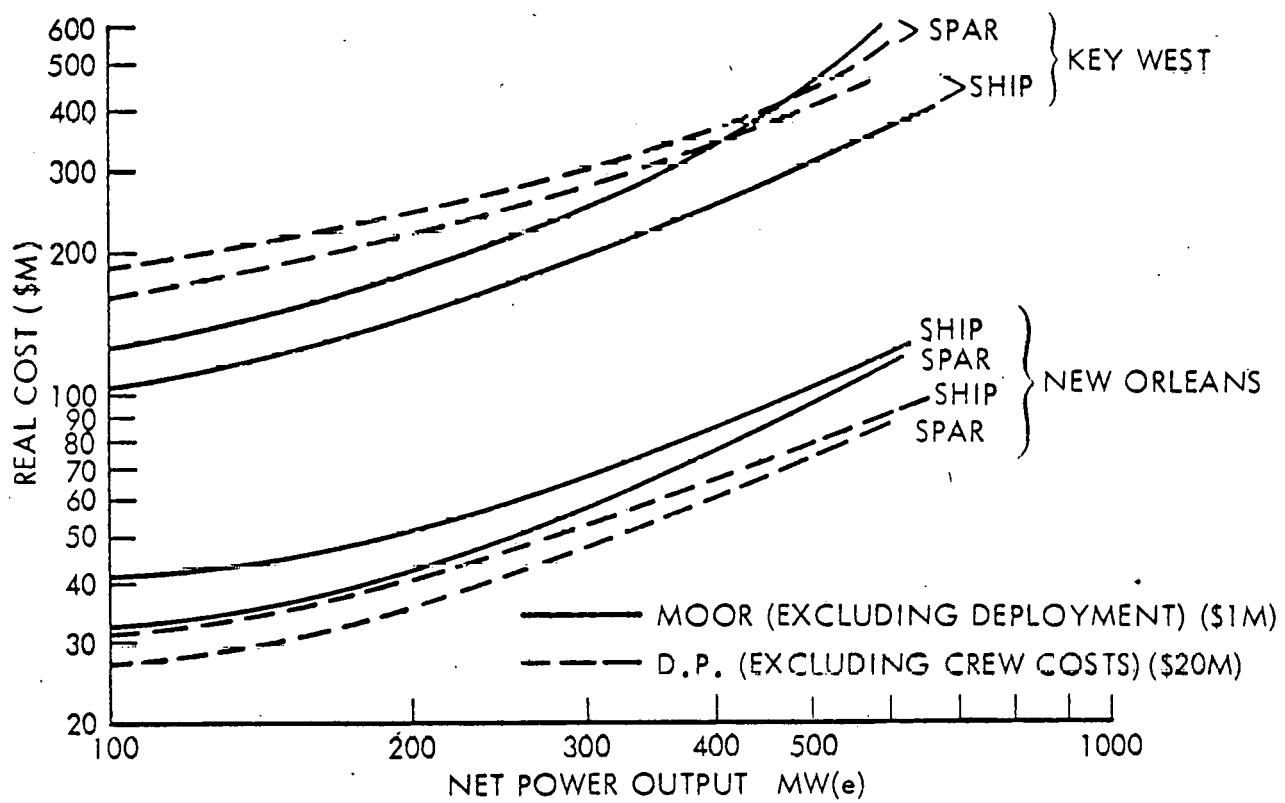
Fig. 2-36 Real Cost of Position-Keeping System

Table 2-35

DYNAMIC POSITIONING FUNCTIONAL COST MODEL

Component	Unit Cost	Cost Function

1. Thrusters
 	
  4000 HP Units
  25 Lb/HP
	$892,000	$8.92 \times 10^5 \times N_{TH}$

2. Annual Fuel Cost
 	
  OTEC Power
  Present Worth Factor (40 Yr)
	
	$0.03/KWHR
	11.925
		$11.925 \times 196 \times \overline{P}$

3. Controls System	2×10^6	2×10^6
P = Maximum Power, = $F_H/25$ $\overline{P}$ = Average Annual Power, = $\overline{F}_H/25$ N_{TH} = Number of Thrusters, = $P/4000 + 1$		

The number of thrusters required varies between 10 for the 100 MW(e) spar in Hawaii to 216 for the 500 MW(e) barge in Key West. Total system costs are found to be less than (by $6M at 100 MW(e)) the cost of a mooring system for the Gulf of Mexico and greater than (by $60M at 100 MW(e)) the mooring system cost for Key West. The variation of dynamic positioning system costs with platform type is observed to be $26M to $31M for 100-MW(e) (net) platforms in New Orleans and $400M to $450M for 500-MW(e) (net) platform in Key West. The power requirements for the thrusters are assumed to be provided by the OTEC power system under all conditions. In the extreme, or 100-year environmental loads, the number of thrusters that can be powered is $100 \times 1000/(4000 \times 0.7457)$, or 33 thrusters, assuming 100 MW(e) (net) output in this condition. There is insufficient power to position any platform in Key West, so that dynamic positioning is not feasible for this site. It is noted that disruption of the thermal resource accompanies extreme sea conditions indicating that full plant output may not be available when required. Auxiliary power supplies would therefore be required.

The cost models do not include crew costs required for maintenance and occasional manual operation of the thrusters or of the tensioning winches on the mooring system. Although these costs are significant over the life of the plant (estimate of $20M for the D.P. system), they are assumed to be included in operational costs.

2.3.4.4 References.

1. Westinghouse Electric Corporation Oceanic Division, Ocean Thermal Power Plants, Cold Water Pipe, Seawater Pumps, and Platform Station Keeping, ERDA Contract No. E(11-1)4071, dtd 27 Sep 1977, pp. 4-6

2. Science Applications, Inc., OTEC Cold Water Pipe Hydrodynamic Loads, by D. T. Hove and W.C.L. Shik, SAI-76-548-LA, 8 Dec 1976

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6. OTEC Platform Configuration and Integration, Environmental Data Package, Jul 14, 1977, (Rev. 1 Aug. 2)

2.4 PLATFORM OPTIONS

OTEC commercial plants have been arranged in six-types of hulls utilizing the specified, baseline internally-mounted, power system as defined and discussed in Section 2.3.1. Arrangements with the baseline power system were made for plants with net output of 100, 200, and 500 MW(e). These eighteen platform arrangements provide the basis for functional models representing the commercial plants. These models are used to define the cost and the size of similar platforms for the purposes of this study.

The costs for the platforms include all major subsystems including the cost of deployment of the platform and the cold water pipe. These costs are considered valid for comparative purposes among the six platform types and as a function of platform size since they are all based on the same specified internally-mounted power system.

Lower platform costs are expected for platforms which fully optimize the platform subsystems in conjunction with the power system and the electrical transmission system. Areas of potential cost optimizations are discussed for each of these platforms and in Sections 3 and 4. One new candidate arrangement (detachable module spar) has been examined because of its potential for producing a lower cost platform than for an internally mounted power system. The other platforms were surveyed and were determined to be unlikely of significant improvement by utilization of a detachable module.

The characteristics of the seven platforms in steel and in concrete for OTEC commercial plants are summarized in this section.
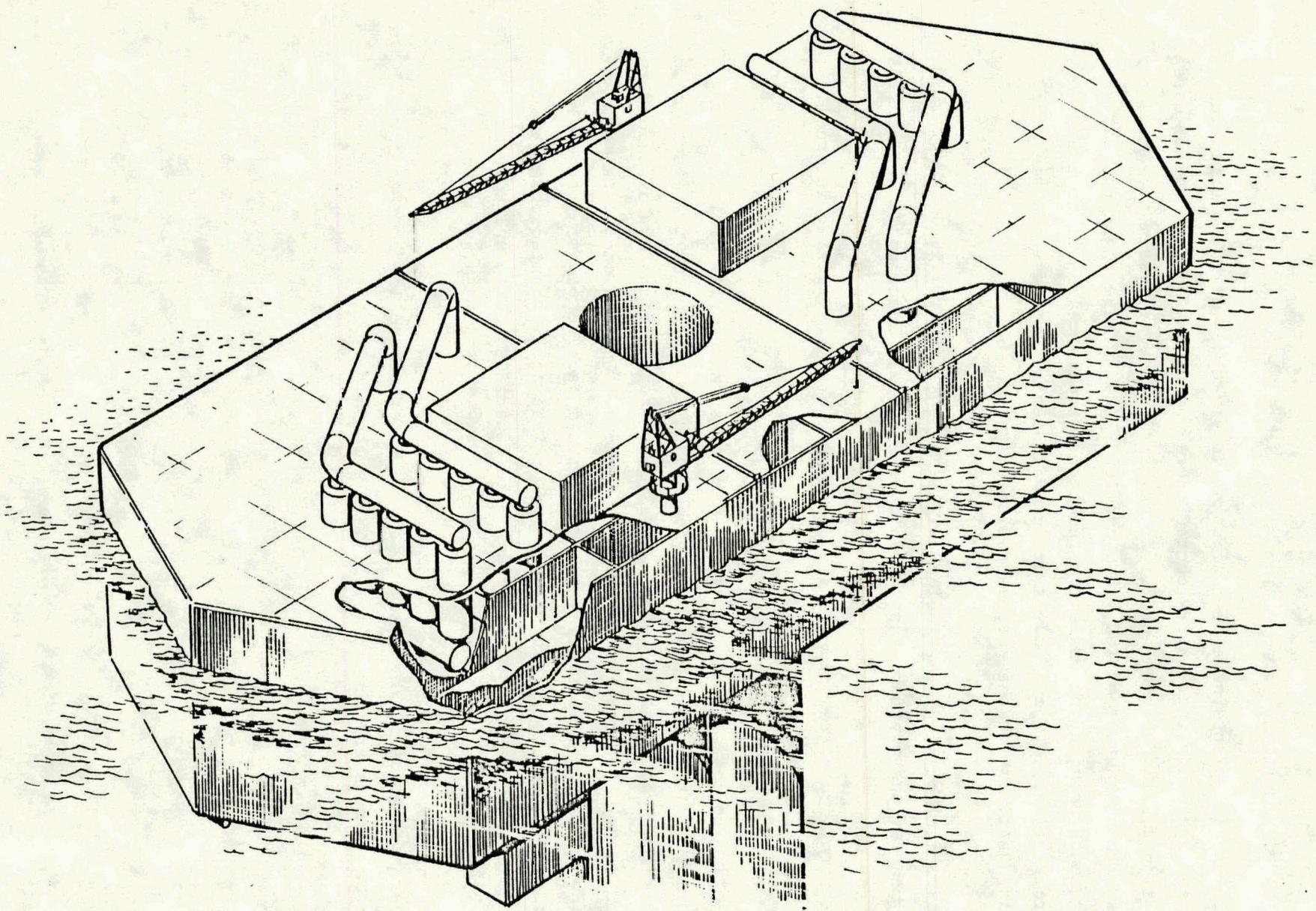
Fig. 2-37 OTEC Ship Configuration for 100-MW(e) (Net) Commercial Plant

2.4.1 Ship Configuration

2.4.1.1 <u>General Description.</u> The 100-MW(e) ship configuration is presented in Fig. 2-38; 200-MW(e) and 500-MW(e) configurations are represented in Table 2-36. Major sizing data and general arrangements are shown in keeping with the preconceptual nature of the present phase of the OTEC Study. A summary of the key sizing data for the three platforms is presented in Table 2-36.

The proposed 100-MW(e) OTEC Ship is essentially a hollow rectangular box with a water distribution system around the perimeter. The simplicity of the arrangement allows easy modifications of the basic geometry of the ship to accommodate component growth or changes to the power plant module from 25-MW(e) to any other combination prior to construction. Previous studies by Lockheed indicate that smaller module size will mean larger required total volume for the net power output. Therefore, smaller modules and/or component growth would mean a larger ship would be required, although the same concept could be retained. Reorientation of the heat exchangers to a fore-aft direction, or use of vertical heat exchangers, would radically change the seawater system. The Ship concept would have to be redesigned to accommodate these changes.

The 200-MW(e) OTEC Ship is identical in arrangement to the 100-MW(e) ship except that the length has been increased to accommodate the larger CWP and the extra 100-MW(e) of equipment, and the width of the wing tanks has been doubled to allow for twice the water flow.
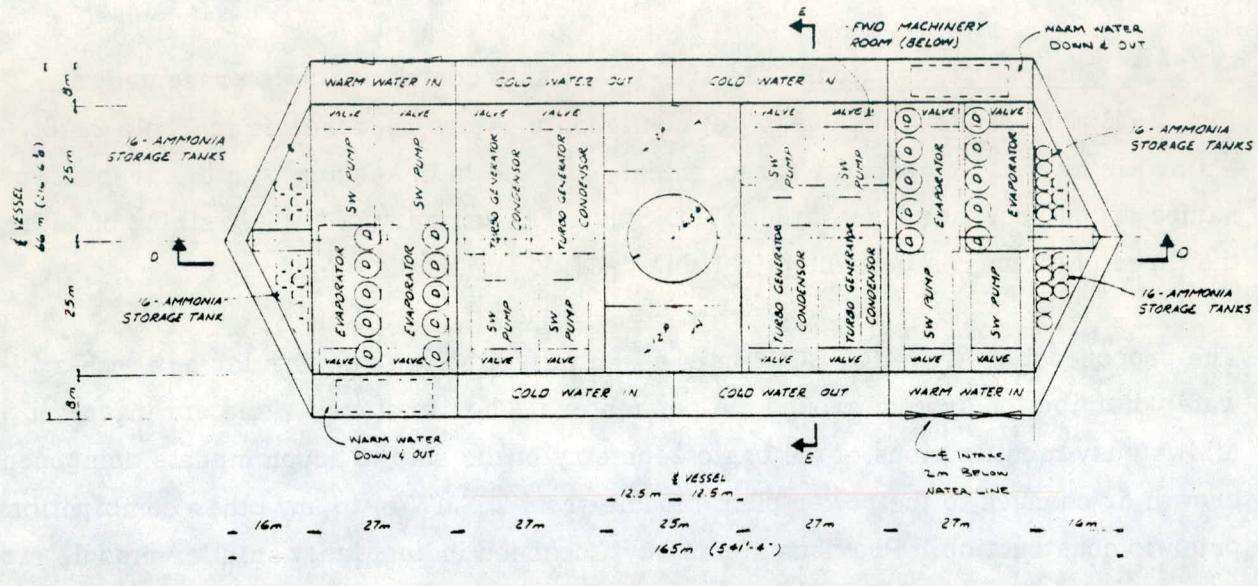
INNERBOTTOM - PLAN A-A
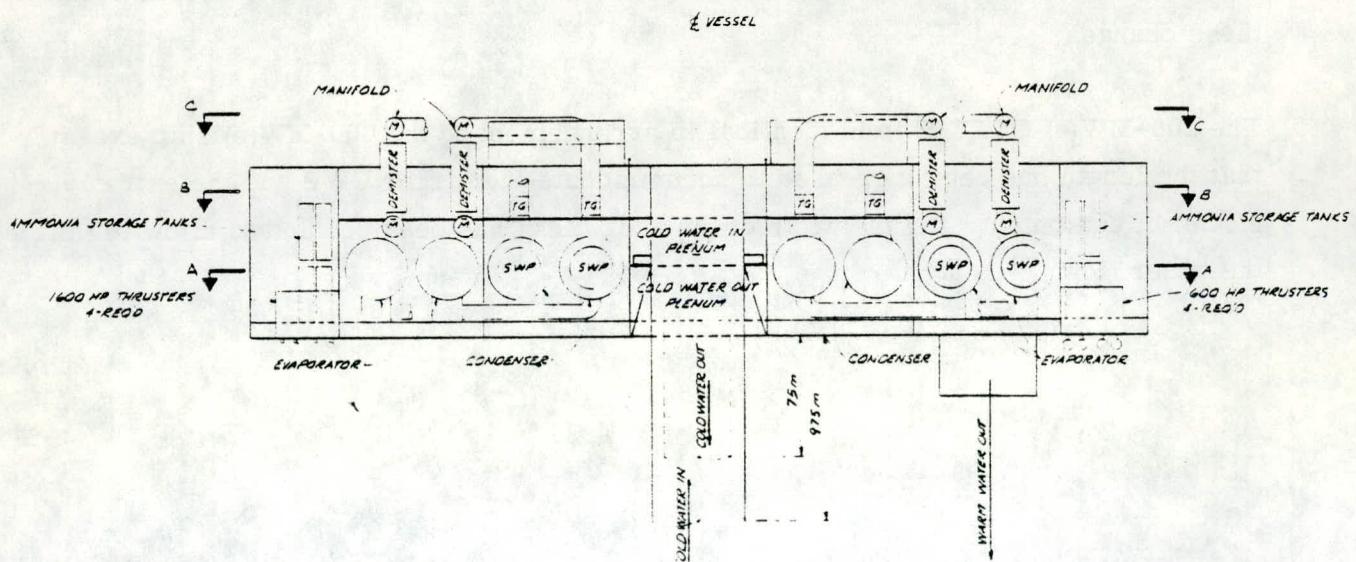
Fig. 2-38 Ship-100 MW(e) (Net) Steel

Table 2-36

PRINCIPAL CHARACTERISTICS OF 100, 200 AND 500 MW(e) (NET) SHIP

Item	SHIP		
	100 MW(e)	200 MW(e)	500 MW(e)
Length (Width) (m)	165	305	356
Breadth (m)	66	82	82
Height (m)	32	32	56
Draft (m)	25	25	48
Displacement (MT)	274,000	630,000	1,500,000
Cost (x 10^{-6})	$ 233	$ 482	$ 984
Cost/KWe	$2,330	$2,410	$1,970

The 500-MW(e) Ship is similar to the 100-MW(e) Ship in operating concept. However, in this arrangement, the heat exchangers are stacked two high. Stacking the heat exchangers causes a significant increase in operating draft, but allows the geometry of the Ship to maintain conventional shipshape proportions.

Hydrostatic properties for the 100-MW(e) platform were computed for the vessel with and without the CWP attached. The curves of form are produced on Fig. 2-39. All values plotted reflect the molded volume of the vessel. The 100-MW(e) OTEC Ship weight summary is presented in Table 2-37.

2.4.1.2 Design Features. The ship is wall-sided throughout for ease of construction and flexibility in equipment placement. The departure from a normal streamlined hull shape will not be a significant disadvantage, since the vessel will never be under way after initial deployment, and the mooring system design is predicated on survival at the worst possible heading to the environment. This last requirement results from the assumption of power loss of the heading control system in the survival condition.

The scantlings have been sized using steel throughout. When the OTEC Ship is actually designed, weight might be minimized to allow for shallow draft construction; however, since additional weight must be added to the vessel to reach operating draft, mild steel was selected over the higher strength steels available for ship construction. With an adequate cathodic protection system, and proper detailed design, the OTEC Ship can be designed and constructed of steel to meet a 40-yr life.

The hull is enclosed by non-tight structural cofferdams on all sides. The bottom of the ship and the forward and aft ends are enclosed by watertight cofferdams. The main deck and the inner bottom are similarly framed. Main frames spanning the full width or depth of cofferdams are oriented transversely to the ship. These are crossed by intermittent longitudinal members of full cofferdam width or depth. Between the full depth longitudinals, the spaces are divided by longitudinal stiffeners on each face of cofferdam. The interior space is partitioned by transverse walls and truss framing which support the main deck.

DISPLACEMENT IN SEA WATER - METRIC TONS

MOLDED DRAFT - METER

KMT

KB

KML

TPm

KB = HEIGHT OF CENTER OF BOUYANCY (ABL) - METER

KMT & KML = TRANSV. & LONGL METACENTER (ABL) - METER

TPm = TONS PER METER IMMERSION - METRIC TONS
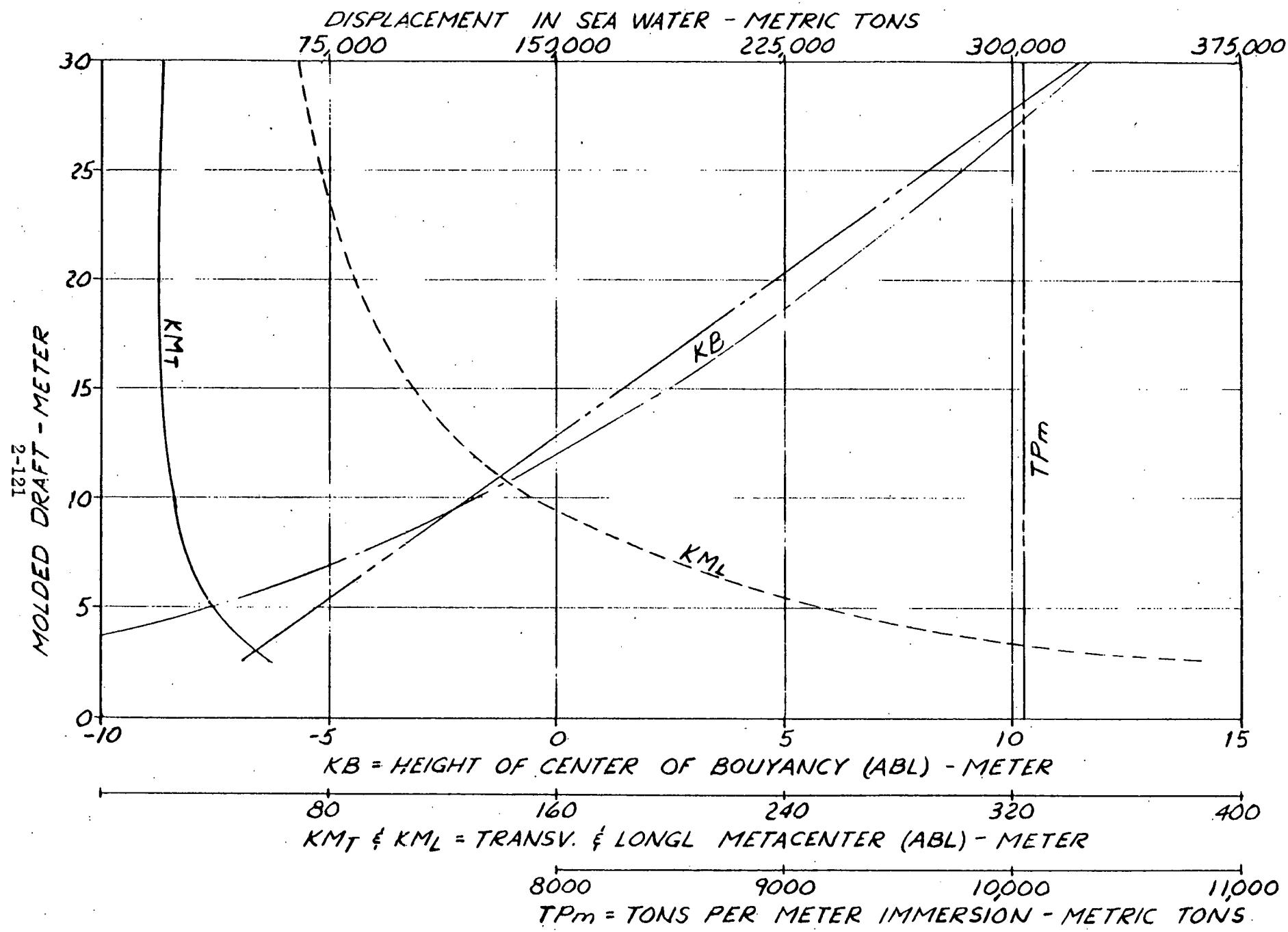
Fig. 2-39   OTEC Ship 100 MW(e) (Net) Curves of Form

Table 2-37

OTEC SHIP WEIGHT SUMMARY

			LIGHTSHIP WEIGHT METRIC TONS	OPERATING WEIGHT METRIC TONS
0.1	**OTEC PLATFORM**			
1.0	HULL AND STRUCTURE			
	1.1	Shell	17,400	17,400
	1.2	Bulkhead	8,300	8,300
	1.3	Decks	4,600	4,600
	1.4	Platforms	2,000	2,000
	1.5	Deck House	500	500
	1.6	Not Used		
	1.7	Not Used		
	1.8	Foundations		
	1.8.1	Cold Water Pipe	2,500	2,500
	1.8.2	Equipment	4,700	4,700
	1.9	Misc. Weights		
	1.9.1	Fixed Ballast	45,000	45,000
	1.9.2	Free Flooding Seawater		96,000
		TOTAL	85,000	181,000
2.0	SEAWATER SYSTEM			
	2.1	Cold Water Pipe	56,800	24,400
	2.2	Cold Water Pumps (4)	700	700
	2.3	Not Used		
	2.4	Warm Water Pumps (4)	700	700
	2.5	Water Ducts		
	2.5.1	Cold Water	3,000	2,000
	2.5.2	Warm Water	0	0
		TOTAL	61,200	27,800

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Table 2-37 (Continued)

3.0   POSITION CONTROL SYSTEM

    3.1   Mooring

    3.2   Thrusters

3.2 Thrusters	500	500
TOTAL	500	500

4.0 SUPPORT SUBSYSTEMS	3,500	3,500
5.0 OUTFIT AND FURNISHINGS	1,500	1,000
TOTAL PLATFORM WEIGHTS	151,200	213,900

0.2   ENERGY TRANSFER SYSTEM   200   200

0.3   POWER SYSTEM

1.0 HEAT EXCHANGERS (8)	16,500	27,390
2.0 TURBO-GENERATORS (4)	820	820
3.0 DEMISTERS (20)	830	860

4.0   AMMONIA SYSTEM

4.1 Vapor Piping	140	150
4.2 Liquid Piping	90	300
4.3 Misc. Piping	20	20
4.4 Ammonia Compressor (4)	40	40
4.5 Ammonia Feed Pump (4)	100	100
10.6 Ammonia Vacuum Pump	10	10
4.7 Ammonia Storage Tanks (64)	1,050	2,610
TOTAL - POWER SYSTEM	19,600MT	32,300MT

0.4   MISCELLANEOUS

1.0 SEAWATER BALLAST		20,000
2.0 CONSUMABLES		5,000
3.0 CWP INSTALLATION CRANE	3,000	3,000
TOTAL MISCELLANEOUS	3,000	28,000
TOTAL WEIGHT WITH CWP	174,000MT	274,000MT
TOTAL WEIGHT WITHOUT CWP	117,200MT	249,600MT

The seawater system consists of the cold water intake pipe (CWP), cold water discharge pipe, warm water intake and discharge systems, seawater plenums, piping, pumps and valves. The CWP conducts water up from a depth of 1,000 m to the cold water intake plenum, located in the center of the vessel and extends transversely between the wing walls. The cold water flows from this vented plenum to wing tanks, and then through butterfly valves into the saltwater pumps. After passing through the pumps and condensers, the cold water exits through another valve into the opposite wing tank. It then flows into the cold water discharge plenum, located directly below the intake plenum, and out through two cold water discharge pipes which extend 75 m below the hull to a depth of 100 m.

The warm water intake is provided through the side of the hull into wing tanks forward and aft of the cold water system. The warm water pumps pump the water through the evaporators and out into the opposite wing tanks. From here the warm water is discharged down through two 8-m-diam. pipes extending 20 m below the hull to a depth of 45 m. The use of wing tanks for the seawater distribution system eliminates the need for internal seawater pipes and provides damage protection without further penalty on hull displacement. It is anticipated that transverse mounting of the pumps and heat exchangers will be acceptable, since roll will be minimized by the vessel's large beam and its ability to orient into the prevailing seas.

The ship will be held on location by a fixed mooring system. This system will limit excursion to acceptable limits as dictated by the electrical transmisssion cable requirements. Heading control will be accomplished by use of the thrusters located below the ends of the hull possibly combined with selective manipulation of mooring line lengths. The goals of heading control will be to minimize environmental forces, minimize adverse motions, and provide warm water intake from an optimum direction with respect to current flow.

The electrical power transmission equipment is located on the Second Deck at the center of the ship above the cold water plenum. The power cables will transit through the hull from a common junction box.

The heat exchanges for the closed loop ammonia power system are on the inner bottom of the ship. The ammonia vaporized in the evaporator passes through the demisters which are mounted on top of the evaporator and penetrate the main deck of the ship. The dry vapor from the demisters are manifolded together and the routed above the main deck directly over the turbine generators. The vapor piping then penetrates the main deck and passes through the turbine generator and into the condenser. The condensed ammonia is then pumped back to the evaporator to complete the cycle. The OTEC Ship has a total of 440 m of ammonia vapor piping and 180 m of ammonia liquid piping. The main power system auxiliaries are located within the hull of the ship. The ammonia storage tanks are located in the forepeak and after peak sections of the ship. They are segregated from the rest of the vessel by watertight bulkheads. The inert gas system is located below the aft port seawater pump on the lower deck level.

2.4.1.3 Constructability.

(a) Facility Requirements

Due to the wide beam of the ship, 66 m (217 ft), none of the facilities surveyed is of sufficient size in which to construct the ship as a single unit. The General Dynamics, Quincy Division, yard has two graving docks adjacent to each other, separated by a wall. If this wall is removed the resulting dock is 267 m × 92 m (874.5 × 300 ft) wide and 6.7 m (22 ft) draft. This is of sufficient size in which to build either the shell only or the hull plus machinery. After launch a protected water site with 22 m (72 ft) water depth is required for adding permanent ballast.

Numerous existing facilities could be used if the construction was started on barges at a shore site adjacent to the shipyard. A barge platform capable of supporting the hull until the watertight shell could be built would have dimensions of 183 m × 76 m (600 ft × 250 ft). Since barges can be moved to deeper water and deballasted to float the ship,

and the ship then towed back for completion of the construction, a minimum shore site draft of 6.6 m (21.5 ft) would be required for the barge construction option.

If a new facility were built it should have the following dimensions:

Width: 76 m (250 ft)
Length: 183 m (600 ft)
Depth: 9 m (30 ft)

This would allow the Ship to be completed except for the installation of the permanent ballast.

A summary of required facilities is presented in Table 2-38.

(b) Construction Methods

Four construction options were considered applicable for the OTEC Ship. These methods are described below. Option I is shown pictorially on Figure 2-40. A summary of the percent of construction completed in each phase is shown in Table 2-39.

(1) Option I — Graving dock construction.
By removing the separating wall at the General Dynamics Quincy Division, 22 ft graving docks that are 149.33 and 150.33 ft wide by 874.5 ft long, a single dock 874.5 × 300 × 22 ft results. The ship can be constructed in this dock, including structure, equipment (dry), and auxiliary machinery. Seawater ducts and tanks are used to reduce draft. Launch draft is 6.6 m (21.5 ft). At an adjacent sheltered water site, the ship outfitting is completed except for installation of the permanent ballast, and the draft of the ship is 22 m (72 ft). Seawater ducts are opened and tanks flooded. In deep water, the CWP is installed.

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Table 2-38

SUMMARY - REQUIRED FACILITIES

	Size	Draft	Facility	Sheltered Water Depth
Drydock - Hull shell only	165x66m	3.9m	GD,Quincy or New	22m
Hull and Machinery	165x66m	6.6m	GD,Qunicy or New	22m
Barge	183x76m	6.2m	Many yards	22m

DRY DOCK (DEPTH ≈ 6.7m)

Remove the separating wall at the General Dynamics Quincy Division graving docks, to create a single dock 267 m × 91m × 6.7m (22 ft). The ship including structure, equipment (car,) auxiliary machinery without the 3000ᵗ crane is constructed in the dock. The draft at float-out is 21.5 ft. Sea water ducts are closed

EXISTING WALL
G.D. QUINCY DOCK ENLARGED

165 m

66 m / 91 m

267 m

DRAFT = 6.6 m (21.5')
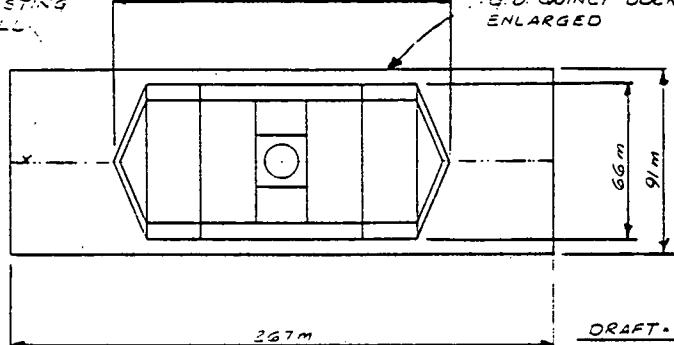
SHELTERED WATER (DEPTH ≈ 80')

In sheltered shallow water the concrete ballast and crane are added and outfitting completed. The side and center tanks are flooded. Sea water ducts are opened. Draft = 22 m (72')
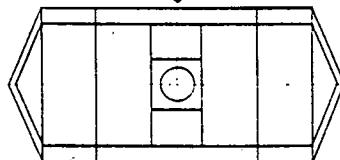
Using the onboard crane install the CWP

DEEP WATER (DEPTH ≈ 1000')

CWP
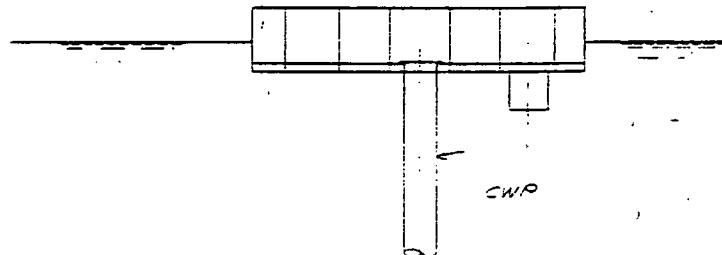
Fig. 2-40 Ship-100 MW(e) (Net) Steel

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Table 2-39

SUMMARY OF CONSTRUCTION METHODS

| | | Single Unit Construction | | | On-Barge Construction |
		Option I	Option II	Option IV	Option III
DRY DOCK	Draft Required	6.6m (21.5')	3.9m (13')	6.6m (21.5')	
	Facility Required	165x66m (541x217')	165x66m (541x217')	165x66m (541x217')	
		Enlarged Existing	Enlarged Existing	New	–
	Flotation	None	None	None	
	Work Portion	91.7%	35.7%	91.7%	
	Work Completed	91.7%	35.7%	91.7%	
SHORE SITE	Draft Required		6.6m (21.5')	22m (72')	6.2m (20.5')
	Flotation		None	None	183x76m (600x250')
		–			Barge
	Work Portion		56%	8.3%	91.7%
	Work Completed		91.7%	100%	91.7%
SHELTERED WATER	Draft Required	22m (72')	22m (72')		22m (72')
	Flotation	None	None	–	Barge
	Work Portion	8.3%	8.3%		8.3%
	Work Completed	100%*	100%*		100%*

* Excluding mobilization — CWP installation, crane installation and removal, towing.

(2) Option II – Dock construction of empty hull.

Within the enlarged dock described in Option I, the Ship's hull
alone is constructed without upper deck leaving the ship's com-
partments accessible from above. The vessel draft is 3.9 m
(13 ft). After float-out into an adjacent shore-site facility the
power plant and auxiliary machinery, and upper deck are installed,
followed by outfitting and crane installation. The draft at this
time is 6.6 m (21.5 ft). The vessel is towed to a protected deep
water site where the permanent ballast is installed and tanks
flooded. This method would allow existing floating cranes to
install the large seawater and power system components and
could possibly save considerable time in construction over
Option I unless heavy lift cranes were available at the graving
dock.

(3) Option III – On-barge construction.

Barge modules are assembled in shallow water to form a 183 × 76 m
(600 × 250 ft) floating platform on which the Ship's shell is con-
structed. When the watertight shell is completed, the barges are
sunk and the ship floated. Installation of the power system,
seawater system, and auxiliary equipment is completed with the
vessel at a 10.4 m draft (34 ft). The vessel is then towed to a
protected water site where the permanent ballast is added
burying the vessel draft to 22 m (72 ft). The CWP is installed at
the OTEC site.

(4) Option IV – Construction in new 30-ft drydock.

A 183 × 76 m (600 × 250 ft), 30-ft-deep drydock is constructed.
The ship is built in this dock, including structure, power plant,
and accessories and crane. Draft is 10.4 m (34 ft) after flooding
of the dock. In sheltered water, the outfitting is completed and
concrete added to a draft of 22 m (72 ft). The CWP is installed
in deep water.

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2.4.1.4 Operability.

(a) Maintenance

The OTEC Ship's internal geometry and equipment arrangement will make on-site maintenance and repair relatively easy. All power system, seawater system, electrical transmission system, and vessel service systems are accessible from within the hull of the Ship. On-board workshops will handle all minor repair items, and there is sufficient room near all the equipment to allow major overhaul work to be performed on board the vessel.

If the ship is part of an OTEC farm, it is possible that all major repair work will be done on a mobile support vessel which is equipped with extensive machine shops and repair facilities. In this case all major components on the Ship except for the heat exchangers can be removed without major impact to the plant operation.

Periodically, the heat exchanges will have to be retubed. The present arrangement allows enough room for the retubing to be done in place. If the heat exchanges must be removed, a gantry crane can be temporarily installed to lift the heat exchanger onto the Main Deck of the vessel. A barge crane could then remove the unit from the ship for retubing. The heat exchangers would be reinstalled in a similar manner.

(b) Operation

Once the Ship is moored in position, the OTEC plant will be similar in operation to an offshore oil and gas production facility except on a larger scale. Manning requirements and schedules, equipment monitoring and maintenance, and the continual checking for dangerous gas or vapor leaks will be similar in both types of facilities. Startup, shutdown, and emergency evacuation procedures for both offshore oil production and OTEC plants will also be of similar complexity and importance.

The operation of the OTEC Ship should not present any significant deviation from procedures which have already proven to be acceptable in numerous offshore installation.

(c) Performance

The Ship platform is designed to satisfy the requirements of the American Bureau of Shipping. ABS measures intact stability by the ability of the vessel to withstand the overturning forces of a severe wind and accompanying waves.

A measure of the stability of the intact vessel is a comparison between the overturning energy created by wind and waves and the righting energy created by the heeled vessel. The amount by which the righting energy exceeds the overturning energy up to the limiting angle is a measure of the vessel's ability to resist capsizing or downflooding. The ABS rules require that the area under the righting moment curve by at least 40% greater than the area under the heeling moment curve up to some limiting angle. The heeling moment curve used is that of a 51.5 m/sec (100 knots) beam wind which decreases as cosine of the heel angle. The limiting angle is that corresponding to either the second intersection of the two curves, beyond which the overturning moment exceeds the righting moment, or the occurence of downflooding, whichever is less.

The intact stability of the vessel has been evaluated for three conditions:

● Light draft (in transit)
● Operating draft (25 m)
● Operating mode: CWP breaks off

For each case, the KG value was calculated. In each case, the area ratio between the righting moment and the heeling moment curves was greater than 1.4. The vessel has sufficient stability in the intact condition to withstand anticipated environmental loads to a degree established as acceptable by ABS.

The amplitude of the significant motions of the 100-MW(e) ship and the attached cold water pipe are presented in Table 2-40.

2.4.1.5 Risks. A potential risk area which may have a bearing on power availability is due to the possible adverse affect of the ship's sensitivity to wave motion on heat exchanger performance, habitability, fatigue loading on the CWP, and application of large bending moment at the pipe-hull interface.

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Table 2-40

CALCULATED SEAWAY RESPONSE FOR SHIP PLATFORM
IN HEAD AND BEAM SEAS, CONCRETE CWP,
$E = 0.3 \times 10^6$ PSI, 10^9 LB-FT/RADIAN
CWP ATTACHMENT STIFFNESS

Response	Units	Significant Amplitude for Significant Wave Height			
		20 ft	35.9 ft	45.8 ft	58.1 ft
HEAD SEAS					
Surge	ft	1.6	5.7	8.7	14.6
Heave	ft	1.4	7.4	11.7	20.1
Pitch	deg	0.6	2.6	4.0	6.2
Max. Acceleration	ft/sec^2	0.7	2.9	4.2	6.1
CWP Rotation	deg	0.6	2.6	3.9	6.4
Max. Bending Moment	lb-ft	9.91×10^7	3.88×10^8	5.83×10^8	8.57×10^8
Max. Bending Stress	psi	1.45×10^2	5.66×10^2	8.5×10^2	1.25×10^3
Max. Shear Force	lb	6.11×10^5	1.62×10^6	2.39×10^6	3.53×10^6
BEAM SEAS					
Sway	ft	2.6	6.8	9.7	15.3
Heave	ft	3.7	14.5	21.4	32.2
Roll	deg	2.2	7.8	11.0	14.8
Max. Acceleration	ft/sec^2	1.9	5.7	7.9	10.2
CWP Rotation	deg	2.1	7.9	11.3	15.5
Max. Bending Moment	lb-ft	2.41×10^8	6.0×10^8	8.62×10^8	1.21×10^9
Max. Bending Stress	psi	3.51×10^2	8.75×10^2	1.26×10^3	1.77×10^3
Max. Shear Force	lb	1.32×10^6	2.95×10^6	4.07×10^6	5.54×10^6

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2.4.1.6 Costs.

(a) Construction Cost – SHIP

The estimated costs to construct the OTEC ship in an existing facility assuming no draft, width, or length limitations are shown in Table 2-41. This is the basic cost to build a 100-MW(e) Ship. To this basic cost must be added a cost based on the construction method employed in building the Ship.

The following cost factors have been used:

Construction Facility	Cost Factor
Graving Dock	1.0
Shore Site (at Shipyard)	1.25
Protected Water	2.0
Unprotected Waters	3.0
On Site (Mobilization Cost)	--

Using weighting factors based on the percentage of construction at each phase of construction from Table 2-41, a construction cost for each construction option was developed. A summary of these costs is shown in Table 2-42.

(b) Mobilization Costs – General

Mobilization includes the following: installation of the 3000T crane for on-site installation of the CWP, towing to the site, installation of the CWP, and completion of platform construction if required. Mobilization costs are largely affected by down time caused by weather and sea states. Assuming a crane barge can operate in six foot significant seas while performing maximum capacity lifts, downtime can vary from 20% in a Gulf of Mexico environment to 70% in a North Sea environment. Mobilization costs have been estimated over the range between these two extremes.

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Table 2-41

PLATFORM CONSTRUCTION COST – SHIP

1.0	HULL AND STRUCTURE	$/MT	MT	COST (x10⁶)
1.1	Shell	3100	17370	53.9
1.2	Bulkheads	3100	8330	25.8
1.3	Decks	3100	4600	14.3
1.4	Platforms	2600	2000	5.2
1.5	Deckhouses	2600	500	1.3
1.6	Not Used			
1.7	Not Used			
1.8	Foundations	3100	7200	22.3
1.9	Fixed Ballast	115	45000	5.2
	TOTAL		85000	128.0

2.0	NOT USED			

3.0	POSITION CONTROL SYSTEM			
3.1	Thrusters			7.0
	TOTAL			7.0

4.0 SUPPORT SUBSYSTEMS

4.1	Cathodic Protection/Coating	7.4
4.2	Machinery	3.0

- Elevators
- Deck cranes
- Diesel Generators (Quarters)
- Emergency Generators (Quarters)
- Hoists, tuggers, forklifts

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Table 2-41 (Continued)

4.3   Hull Piping Systems/w Machinery   11.0
       • Ballast
       • Bilge
       • De-Ballast Vent
       • Sounding
       • Engine Cooling
       • Compressed Air
       • Lube Oil
       • Fuel Oil
       • Fresh Water

4.4   HVAC   8.2

4.5   Safety Equipment   1.0

       • Fire Protection
       • Lifeboats
       • Life Rafts

4.6   Electrical Work (Misc.)   1.5

4.7   Vessel Management   3.6

4.8   Accomodation   2.5

4.9   Misc. Workshops   1.0

4.10   Radio and Communications   0.2

                                    TOTAL   39.4

5.0   Installation of OFE   500   26,000   13.0
       • DACS
       • Sea Water System
       • Mooring System
       • 3000m Gantry Crane
       • Energy Transfer System
       • Power System

                          Total $187,400,000

Table 2-42

CONSTRUCTION METHOD COSTS – SHIP

Construction Location	Work Description	Option I			Option II			Option III			Option IV		
		Weight	Unit Cost	Cost	Weight	Unit Cost	Cost	Weight	Unit Cost	Cost	Weight	Unit Cost	Cost
DRY DOCK (Cost Factor) = 1	Structure Equip. Instl.	40,000 26,000	3,070 500	122.8 13	25,700	3,070	78.9				40,000 26,000	3,070 500	122.8 13
SHORE SITE (Cost Factor) = 1.25	Structure Equip. Instl.				14,300 26,000	3,070 500	54.9 16.3	40,000 26,000	3,070 500	153.5 16.3			
SHALLOW WATER (Cost Factor) = 2	Structure Equip. Instl. Concrete Ballast	45,000	115	10.4	45,000	115	10.4	45,000	115	10.4	45,000	115	10.4
ON-SITE (Cost Factor) = 3	Structure Equip. Instl. Concrete Ballast												
Subtotal				146.2			160.5			180.2			146.2
Support Subsystem and DP System				46.4			46.4			46.4			46.4
Total				192.6			206.9			226.6			192.6
	Units	mt	$/mt	$ million	mt	$/mt	$ million	mt	$/mt	$ million	mt	$/mt	$ million

Assuming costs of $300,000 day for the installation equipment, assembly crews, and supply/support vessels, and the maximum construction period of 320 days (see Section 2.4.1.7) the basic cost range for mobilizing the OTEC platform will be:

Minimum Cost = $39,900,000
Maximum Cost = $96,000,000

Since all construction of the OTEC ship is planned to be completed within shipyard and shallow water areas no additional mobilization costs above those mentioned need be considered.

Mobilization costs — ship: $40 to 96 million.

2.4.1.7 Schedule. The CWP is expected to weigh 60,000 MT dry and have a length of 1,000 m. If a crane of 200 MT lifting capacity is available there will be 30 lifts, assuming CWP installation is done segment by segment. The procedure envisioned is that a 2,000 MT CWP module will be lifted on board from a supply ship, using a crane on the supply ship or other attendant vessel. The OTEC gantry crane will lift this module and lower it down to the point where the joint can be made up; and then the pipe is lowered, after the joint is made. The following time period estimates are assumed:

Lift Module into Position	1 day
Make Up Joint	1 day
Lower CWP Assembly	1 day

Therefore, with 30 joints at 3 days per joint, the minimum assembly time for the CWP will be 90 days. Applying downtime factors and allowing for transit time of 10 days both ways for the installation support vessels, the minimum and maximum assembly time is as follows:

Minimum Worktime

- Basic CWP Installation   90 days
- Downtime (90/0.8-90)   23 days
- Transit Time (10 + 10)   <u>20 days</u>

           Minimum Time = 133 days

Maximum Worktime

- Basic CWP Installation   90 days
- Downtime (90/0.3-90)   210 days
- Transit Time   <u>20 days</u>

           Maximum Time = 320 days

2.4.1.8 Summary. The ship platform should provide an adequate platform for an OTEC commercial plant if the sensitivity of the power system (principally the heat exchangers) to platform motions does not significantly affect the availability of power from the plant. The use of the wing tank area for sea water ducting is a step in the direction to optimization among the platform systems. Extension of this approach to include the power system and the cold water pipe in an optimization of the plant should lead to further refinements in the hull arrangement and in reduction of the costs of the ship-type platform.

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2.4.2 Circular Barge Configuration

2.4.2.1 <u>General Description</u>. The 100-MW(e) circular barge configuration is presented in Fig. 2-41. The 200-MW(e) and 500-MW(e) configurations are presented in numerical form. Major sizing data and general arrangements are shown in keeping with the pre-conceptual nature of the present phase of the OTEC Study. Significant properties for the three configurations are shown in Table 2-43. Tables 2-44 through 2-46 present weight estimates and preliminary characteristics.

The OTEC plant components, their size and proper relative orientation, was the over-riding consideration in determining the arrangements and the principal dimensions of the platform. The principal dimensions were minimized to reduce construction, main-tenance, and operation costs. In this preliminary stage of the design, the results of naval architecture calculations have not required that changes be made in the OTEC arrangements or platform principal dimensions. Double shell or approximate location of watertight one-compartment subdivision bulkheads were considered in the design of arrangements.

Table 2-43

PRINCIPAL CHARACTERISTICS OF 100-, 200-, AND 500-MW(e) (NET) BARGES

Item	Barge		
	100 MWe	200 MWe	500 MWe
Length (Width) (m)	98	105	149
Breadth (m)	98	105	149
Height (m)	43	50	105
Draft (m)	31	38	91
Displacement (MT)	284,000	416,000	1,660,000
Cost (x 10^{-6})	$ 210	$ 419	$ 1,363
Cost/KWe	$ 2,100	$2,095	$ 2,730

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PLAN VIEW
2ND DECK

SECTION "S-S"
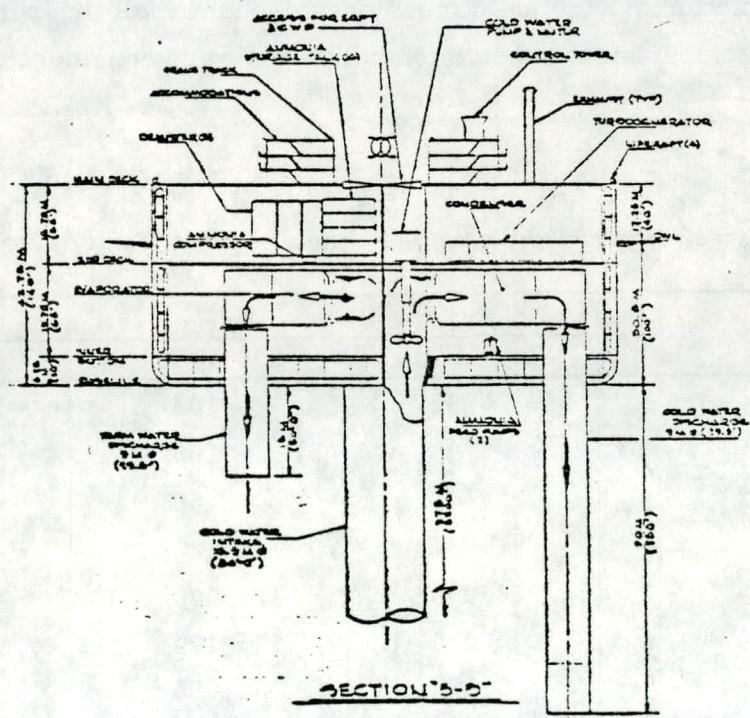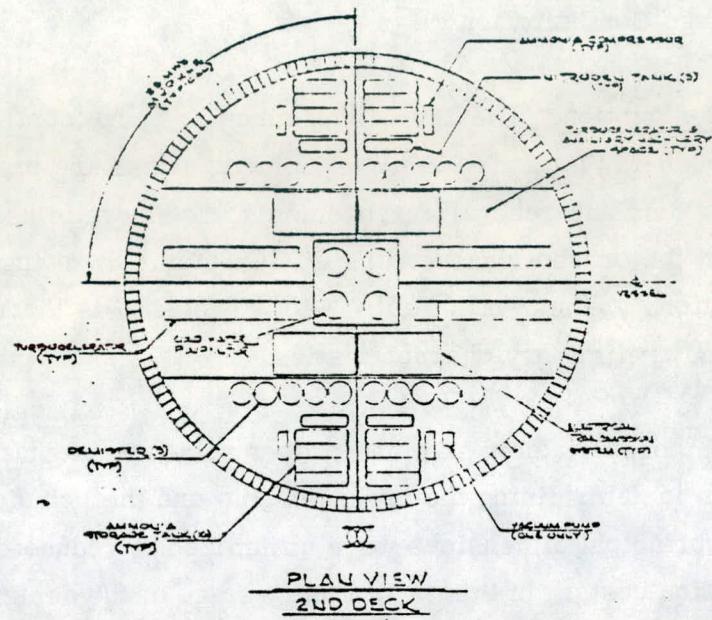
Fig. 2-41 Circular Barge 100 MW(e) (Net) Steel

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Table 2-44
MASS PROPERTIES FOR 100 MW(e) CIRCULAR BARGE

O.D. 97.5 M. (320'); I.D. 91.5 M. (300'); Depth 42.7 M. (140')

Approximate weight estimate and preliminary characteristics:

	METRIC TONNES	LONG TONS
Hull Structure:		
Shell	26,417	26,000
Decks	8,128	8,000
Bulkheads	5,080	5,000
Superstructure	1,016	1,000
Hull Structure	40,641	40,000
Foundations	12,193	12,000
Power System Cold Water Pipe (Dry)	55,883	55,000
Sea Water Piping	6,096	6,000
Fixed Ballast	33,530	33,000
Power System (Dry)	32,514	32,000
Light Ship (Dry)	180,857	178,000
Power System Water (Internal)	15,241	15,000
Power System Water (External)	20,321	20,000
Power System Water (Exchangers)	7,112	7,000
Variable Ballast	60,963	60,000
TOTAL WEIGHT (OPERATING)	284,494	280,000
Tonnes per cm. or Tons per inch	72.08	186
Tonnes per metre or tons per foot	7,208	2,232

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Table 2-44 (Cont.)

	METRE	FEET
Full load mean draft	30.48	100.0
K.G. Without Ballast and CWP	13.72	45.0
K.G. With Ballast and CWP	-46.03	-151.0
K.B.	14.81	48.6
B.M.	20.67	67.8
K.M.	35.48	116.4
G.M. Without Ballast & CWP	21.76	71.4
G.M. With Ballast and CWP	81.51	267.4

Raddi of gyration without CWP or Ballast

	METRE	FEET
R_{xx}	31.10	102.0
R_{yy}	36.00	118.0
R_{zz}	33.53	110.0

Table 2-45
200 MW(e) (NET) OFF-BASELINE DESIGN

3.1 <u>Mass Properties for 200 MWe Circular Barge</u>:

O.D. 105.2 M. (345'); I.D. 99.1 M. (325'); Depth 50.3 M. (165')

Approximate weight estimate and preliminary characteristics:

	METRIC TONNES	LONG TONS
Hull Structure:		
Shell	39,626	39,000
Decks	12,193	12,000
Bulkheads	8,128	8,000
Superstructure	1,016	1,000
Hull Structure	60,963	60,000
Power System Foundations	20,321	20,000
Cold Water Pipe (Dry)	79,252	78,000
Sea Water Piping	10,160	10,000
Fixed Ballast	- 0 -	- 0 -
OTEC Plant (Dry)	65,027	64,000
Light Ship (Dry)	235,723	232,000
OTEC Water (Internal)	28,449	28,000
OTEC Water (External)	34,546	34,000
OTEC Water (Exchangers)	14,225	14,000
Variable Ballast	103,637	102,000
TOTAL WEIGHT (OPERATING)	416,579	410,000
Tonnes per cm. or tons per inch	89.03	223
Tonnes per metre or tons per foot	8,903	2,676
Full load mean draft	38.1 M.	125 ft.

Table 2-46
500 MW(e) CIRCULAR BARGE OFF-BASELINE DESIGN

Mass Properties for 500 MWe Circular Barge:

O.D. 149.4 M. (490 ft.); I.D. 140.21 M. (460 ft.); Depth 105.16 M. (345 ft.)

Approximate weight estimate and preliminary characteristics:

	METRIC TONNES	LONG TONS
Hull Structure:		
Shell	152,407	150,000
Decks	49,786	49,000
Bulkheads	30,481	30,000
Superstructure	2,032	2,000
Hull Structure	234,706	231,000
Power System Foundations	44,706	44,000
Cold Water Pipe (Dry)	124,974	123,000
Sea Water Piping	25,401	25,000
Fixed Ballast	- 0 -	- 0 -
Power System (Dry)	162,568	160,000
Light Ship (Dry)	592,355	583,000
Power System Water (Internal)	170,696	168,000
Power System Water (External)	47,754	47,000
Power System Water (Exchangers)	36,578	36,000
Variable Ballast	812,838	800,000
TOTAL WEIGHT (OPERATING)	1,660,221	1,634,000

Estimated Deep Draft = 91 M. (300 ft.)

Tons per inch = 422 Tons, or 5,064 Tons per foot

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2.4.2.2 <u>Design Features</u>. The main hull envelope will be constructed of ordinary strength steels, welded throughout. A double shell will be provided on the sides and bottom. Higher strength steels will be used as required at the hull/CWP interface and any other critical areas. The side and bottom shell will be framed circumferentially and will have radial webs at selected intervals.

Main watertight bulkheads will be located as shown on the general arrangement drawing. Bulkhead scantlings will be designed with the Main Deck as the bulkhead deck. Details of continuity and tightness of the bulkheads will be developed to provide necessary strength and watertight subdivision.

Strength decks will be located on the Main Deck, 2nd Deck and Innerbottom levels as shown on the general arrangement drawing. Deck penetrations will be compensated by insert plates of extra thickness. Platforms and flats will be provided as required to suit auxiliary machinery arrangements.

A deck house will be provided above the main deck that will contain all accommodations, store spaces, communications and navigation spaces, and miscellaneous service areas. Bulkheads and decks will be steel, and all boundaries will be watertight. The house structures will be supported by the house boundaries, bulkheads, trunks and casings, and by a system of pillars, beams and girders.

Masts and kingposts will be provided as shown on the general arrangement drawing to support the required antenna arrays, aids to navigation, and ventilation systems.

Service platforms, decks and gratings will be included as required to provide access to all equipment for operation and maintenance.

Foundations for the heat exhangers, pumps, tanks, turbogenerators and other heavy equipment will be welded steel construction throughout. Foundation girders and webs will be integrated with the basic hull structure and will have long tapers in reducing to primary structure. Adequate access will be provided in all foundations for cleaning, maintenance and proper operation of equipment. Foundation structures will be designed to act as complete supports for all static and dynamic loads.

2.4.2.3 Constructability. Existing domestic construction facilities include graving docks that will accommodate lengths up to 1200 ft, breadths up to 200 ft and drafts up to 40 ft. The circular barge beam (diameter) is the one critical dimension that will have a major impact on selection of existing facilities. The number of hulls to be constructed would also be of major importance in determining whether to adopt construction methods to existing facilities or incur the cost of a specially built construction yard.

Restricting constructability concepts to existing facilities, it is entirely within the state-of-the-art to build the hull in halves (or in more sections at the option of the contractor) and join the sections afloat. This method of construction has been successfully employed for several years in both domestic and foreign yards for large tankers and floating structures utilized in the offshore oil industry. Shipyards with existing facilities for this type of construction include the Bethlehem-Sparrows Point Yard in Baltimore, Maryland; Sun Shipbuilding and Drydock Co. in Chester, Pa.; Ingalls Shipbuilding Corp. in Pascagoula, Miss.; and National Steel and Shipbuilding Co. in San Diego, Ca.

The construction sequence would provide for bottom shell, double bottom, side shell, and interior decks and bulkheads to be erected in a graving dock up to a depth to be determined by the contractor. Major power system and seawater system components would be installed in timely sequence as the hull is erected. This would continue until the drydock weight limitations or float-out draft limitations were reached.

After float-out, the hull sections would be joined afloat and construction would continue at an outfitting pier or in sheltered waters, depending upon draft limitations. Preliminary weight estimates indicate that the entire hull (excluding the cold and warm water pipe projections) could be completed in this manner within the limits of domestic facilities.

Installation of the cold water intake pipe and the warm and cold water discharge pipes would have to be carried out afloat on-site. Center well access and crane facilities could be provided on-board the barge for installation of the cold water intake pipe in sections. The shorter discharge pipes could be installed from below the hull or by telescoping down from within the hull.

2.4.2.4 Operability. A permanent mooring system will be used to keep the platform on station and minimize loads on the power transmission systems risers. A positioning system of rotatable thrusters will be used to orient the platform so that sea currents at the surface are perpendicular to the intakes for warm water. The positioning system will also orient the platform to minimize loads on the transmission cable and cold water pipe and weather effects on crew comfort.

Because of the size of this platform and the cold water pipe, hull maintenance can not be performed in a normal shipyard. For steel hulls periodic maintenance will be required at 4-yr intervals at the platform moored site. This will require cleaning, sandblasting and painting in artificial dry environment. Underwater vehicles with devices which can scrape off large growth will be required to precede vehicles which move over the surface of the hull and form a large sealed dry space for sandblasting and painting. This will be a continual hull maintenance program so that each area of the submerged hull will be cleaned and painted every 4 yrs. At these periods ultrasonic gaugings will be taken to check for any deterioration of hull material. Cold water and warm water discharges will be made of low-maintenance concrete and should not require maintenance to preserve material.

For periodic maintenance of the OTEC plant components, overhead cranes will be installed from the overhead of each deck to assist in removal, disassembly, reassembly, and reinstallation of large items. The arrangement of each deck allows for removal of major components. Retubing the heat exchanger can be performed in place for one or more power modules while allowing full capacity operation of the remaining power modules. Heat exchangers can be removed and replaced with direct vertical lift access while other power modules are allowed full operating capacity. Servicing of the sea water pump motor is convenient.

The amplitude of significant motions of the 100 MWe circular barge and the loads in the cold water pipe are summarized in Table 2-47.

2.4.2.5 Risks. The primary risk for the circular barge is related to the effect of the platform motions on the cold water pipe and the pipe of hull transition. The barge has the largest heave, surge, sway, and pitch motions of the several platforms and is only exceeded in roll angle by the ship in a beam sea. These motions are reflected in the largest dynamic bending moments being imposed by the barge on the cold water pipe. While some refinements and tuning of the platform/CWP interface can be expected to reduce the currently predicted loads, the trend will still remain. Extensive analysis and design will be required to get a good definition of a CWP that will have long life on the circular barge. The uncertainty in cost, schedule, and technical options for this problem leads to this as a major risk area. The related problem of potential power output degradation with platform motions also reflects the inherent motion characteristics of a surface platform.

Table 2-47

CALCULATED SEAWAY RESPONSE FOR CIRCULAR BARGE PLATFORM
IN HEAD AND BEAM SEAS, CONCRETE CWP, t = 2 FT
E = 0.3×10^6 PSI, 10^9 LB-FT/RADIAN
CWP ATTACHMENT STIFFNESS

Response	Units	Significant Amplitude for Significant Wave Height			
		20 ft	35.9 ft	45.8 ft	58.1 ft
HEAD SEAS					
Surge	ft	2.3	6.4	9.3	15.3
Heave	ft	3.4	17.1	26.1	40.2
Pitch	deg	1.1	4.7	7.3	12.0
Max. Acceleration	ft/sec^2	1.1	3.1	4.6	6.6
CWP Rotation	deg	0.8	3.7	6.5	11.2
Max. Bending Moment	lb-ft	1.58×10^8	4.20×10^8	6.20×10^8	9.6×10^8
Max. Bending Stress	psi	2.30×10^2	6.12×10^2	9.04×10^2	1.40×10^3
Max. Shear Force	lb	7.52×10^5	2.13×10^6	3.20×10^6	4.92×10^6
BEAM SEAS					
Sway	ft				
Heave	ft				
Roll	deg				
Max. Acceleration	ft/sec^2	Essentially the same as Head Seas			
CWP Rotation	deg				
Max. Bending Moment	lb-ft				
Max. Bending Stress	psf				
Max. Shear Force	lb				

2.4.2.6 <u>Costs.</u> Cost estimates for the 100-MW(e), 200-MW(e), and 500-MW(e) platforms are presented in Tables 2-48, 2-49, and 2-50, respectively.

2.4.2.7 <u>Schedule.</u> The estimated span required for construction of the circular barge is 42 months. A further span of 5 months is estimated for deployment of the barge-type commercial plant.

2.4.2.8 <u>Summary.</u> The barge will provide an adequate platform for an OTEC power system if the output is not sensitive to platform motions. The arrangements presented in this comparison study represent a nearly optimum for use of the barge for horizontal heat exchangers. There is ample room for servicing the power system components chiefly because of the arrangement problem encountered with linear elements in a circular envelope. Integration and optimization of the power system, seawater system, and the hull should provide for some small reduction in cost of the platform.

Table 2-48
100 MW(e) (NET) CIRCULAR BARGE COST ESTIMATE

	ITEM	WT.	$/MT	ECF[1]	TOTAL COST
1.	Shell Plating & Stiffeners	26,400	$3100	1.25	$102,300 \times 10^3$
2.	Bulkheads & Stanchions	5,100	3100	1.00	$15,810 \times 10^3$
3.	Decks, Platforms, Flats, Misc. Outfit.	8,100	3100	1.00	$25,100 \times 10^3$
4.	Superstructure	1,000	2600	2.00	$5,200 \times 10^3$
5.	Power System Foundations	12,200	3100	1.00	$37,820 \times 10^3$
6.	Warm and Cold Water Pipes	2,286	3100	3.00	$21,260 \times 10^3$
7.	Accommodations	–	–	–	$2,450 \times 10^3$
				TOTAL	$209,940,000

NOTE: 1. Erection Complexity Factor is used to correct $/MT values for varying construction conditions. We have assigned a factor of 1.0 for erection in graving dock, 2.0 for completion afloat in sheltered water, and 3.0 for all construction required on-site.

2. Total Cost Estimate does not include Power System Cost, Sea Water System costs or Electrical Transmission System Costs.

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Table 2-49
200 MW(e) CIRCULAR BARGE COST ESTIMATE

	ITEM	WT.	$/MT	ECF[1]	TOTAL COST
1.	Hull Shell	39,600	$3,100	1.5	$ 184,100 x 10³
2.	Hull Decks	12,200	3,100	1.5	56,700 x 10³
3.	Hull Bulkheads	8,100	3,100	1.5	37,700 x 10³
4.	Superstructure	1,000	2,600	2.0	5,200 x 10³
5.	Power System Fndn.	20,300	3,100	1.5	94,400 x 10³
6.	Discharge Pipes	4,075	3,100	3.0	37,900 x 10³
7.	Accommodations	–	–	–	2,900 x 10³
				TOTAL	$ 418,900,000

NOTE: 1. Erection Complexity Factor is used to correct $/MT values
for varying construction conditions. We have assigned a
factor of 1.0 for erection in graving dock, 2.0 for com-
pletion afloat in sheltered water, and 3.0 for all construc-
tion required on-site.

2. Total Cost Estimate does not include Power System cost,
Sea Water System costs or Electrical Transmission System
costs.

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Table 2-50
500 MW(e) CIRCULAR BARGE COST ESTIMATES

ITEM	WT.	$/MT	ECF [1]	TOTAL COST
1. Hull	234,700	$3100	1.5	$1,091,400 \times 10^3$
2. Superstructure	2,000	2600	2.0	$10,400 \times 10^3$
3. Power System Fndn	44,700	3100	1.5	$207,900 \times 10^3$
4. Discharge Pipes	5,300	3100	3.0	$49,400 \times 10^3$
5. Accommodations	-	-	-	$3,500 \times 10^3$

TOTAL: $1,362,600,000

NOTE: 1. Erection Complexity Factor is used to correct $/MT values for varying construction conditions. We have assigned a factor of 1.0 for erection in graving dock, 2.0 for completion afloat in sheltered water, and 3.0 for all construction required on-site.

2. Total Cost Estimate does not include Power System cost, Sea Water System costs or electrical Transmission System costs.

2.4.3 Semisubmersible Configuration

2.4.3.1 <u>General Description.</u> The 100-MW(e) semisubmersible configuration is presented in Fig. 2-42; 200 MW(e) and 500 MW(e) configurations are presented in numerical form. Major sizing and general arrangements are shown in keeping with the pre-conceptual nature of this phase of the OTEC study. A summary of the key sizing data for the three platforms is presented in Table 2-51.

The size and configuration of the OTEC Semi is determined by the size of the heat exchangers and seawater pumps. Growth of these components would require an equivalent increase in the Semi dimensions. Reorientation of the major components, such as using vertical heat exchangers, could not be accommodated without major redesign of the Semi-Submersible.

The 200-MW(e) Semi is an enlarged version of the 100-MW(e) Semi. The arrangement and operation of the 200-MW(e) Semi are described in Section 2.4.3.2.

The arrangement of the seawater intakes, discharge, and heat exchangers have been changed on the 500-MW(e) Semi. The heat exchangers are stacked two high with the evaporators above the condensers. The demisters are stored in a raised area which spans the entire width of the hull.

The cost of upgrading an existing facility, or building a new facility, is not included in cost estimates. In the construction option, which builds the platform on floating barges, the cost of the barges are not included in the estimate.

The hydrostatic characteristics of the vessel were calculated manually. The two side pontoons and the center pontoon were taken as lower hull and the free-flooding tanks assumed part of intact hull. The effect of water in free-flooding tanks takes as weight on the vessel. The weight of CWP in water was included in obtaining the total displacement. The hydrostatic properties were computed for the vessel with and without the CWP attached.

2-156
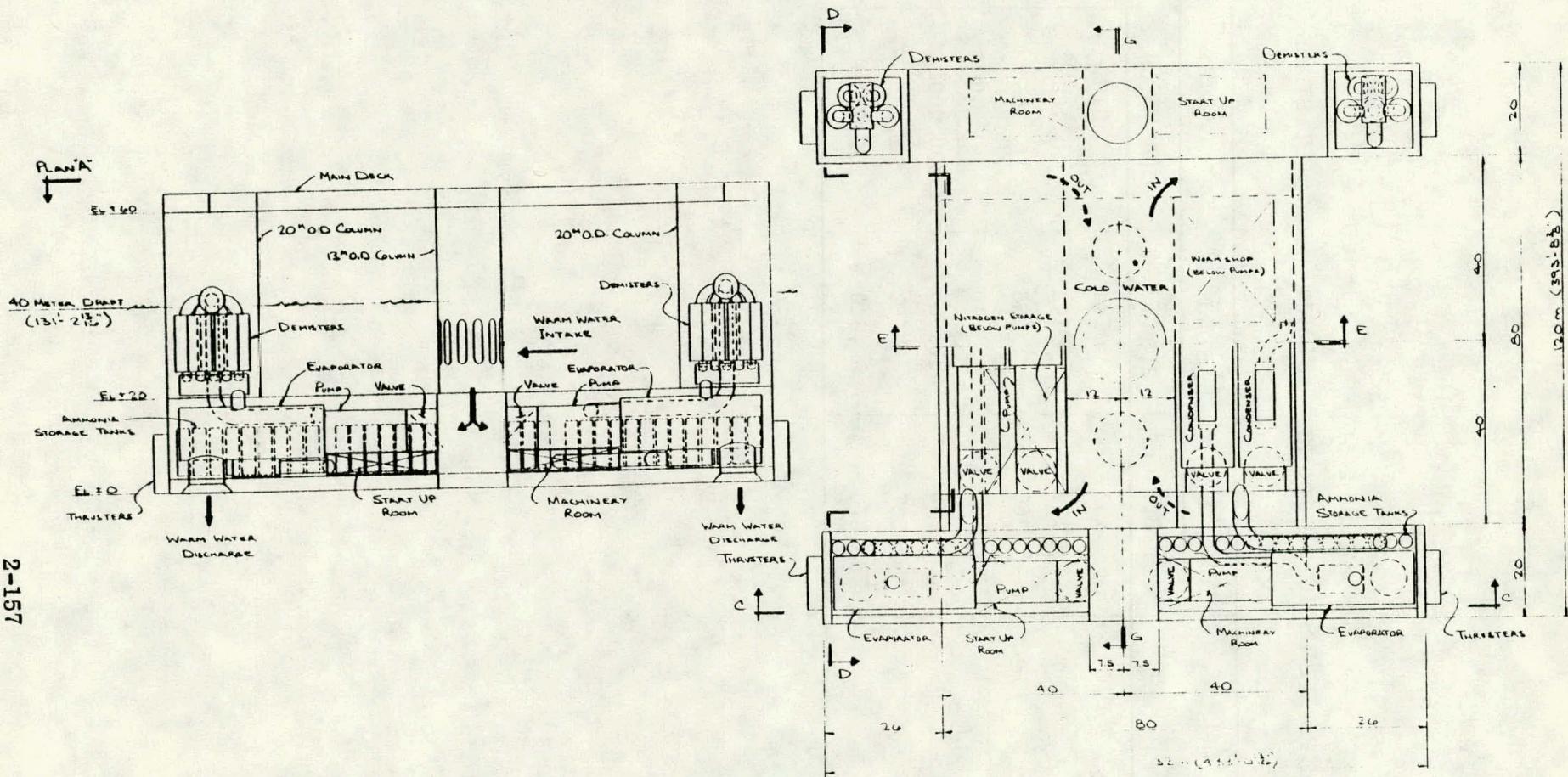
Fig. 2-42 Semi-Submersible 100 MW(e) (Net) Steel

Table 2-51

PRINCIPAL CHARACTERISTICS OF 100, 200 AND 500 MW(e) (NET) SEMIS

Item	SEMI		
	100 MW(e)	200 MW(e)	500 MW(e)
Length (Width) (m)	132	144	216
Breadth (m)	120	142	162
Height (m)	65	65	105
Draft (m)	40	40	40
Displacement (MT)	350,000	590,000	1,690,000
Cost ($\times 10^{-6}$)	$ 337	$ 562	$ 1,265
Cost/KW	$3,370	$2,810	$2,530

The curves of form are produced on Fig. 2-43. All values plotted reflect the molded volume of the vessel.

The 100-MW(e) Semi weight summary is presented in Table 2-52.

2.4.3.2 Design Features. The Semi platform consists of:

- A central submerged hull, 90m × 80m × 28m, containing the cold water system and condensers
- Two "pontoons" each 20m × 20m × 152m attached to the sides of the control hulls and housing the warm water system and evaporators
- Four 20-m-diam. stability columns extending up from the ends of the pontoons
- Two 13-m-diam. columns at the pontoon centers, providing warm water intake
- A single 20-m central column providing venting for the cold water system
- A deck structure supporting deck houses and crane facilities

The scantlings have been sized for mild steel throughout. Unlike the Ship, the Semi will require special through-thickness quality steel at the major hull-to-hull and hull-to-column connections to ensure an adequate life for these connections. This special steel will also be used at the main deck to column connections. The Semi, like the Ship and the Spar, can be designed to meet a 40-yr operating life.

The hull structure is enclosed by structural cofferdams on all exterior surfaces. The hull top and bottom are similarly framed. Main frames spanning the full width or depth of cofferdams form a grid which supports plate stiffeners on both faces of the cofferdam. Main frames are oriented transversely in the hull top and bottom of the mid hull and pontoons. They continue up the side shell, forming ring frames encircling the mid-hull and pontoons. These frames are crossed by intermittent longitudinal members of full cofferdam width or depth. Where they continue up the fore and aft shell cofferdams, they are crossed by horizontals the full width of the cofferdam. Between these longitudinals, the spaces are divided by longitudinal plate stiffeners on each face of the cofferdams. In the fore and aft cofferdams, these stiffeners are located vertically.

DISPLACEMENT IN SEA WATER - METRIC TONS

KB = HEIGHT OF CENTER OF BOUYANCY (ABL) - METER

KM_T & KM_L = TRANSV. & LONGL. METACENTER (ABL) - METER

TPm = TONS PER METER IMMERSION - METRIC TONS
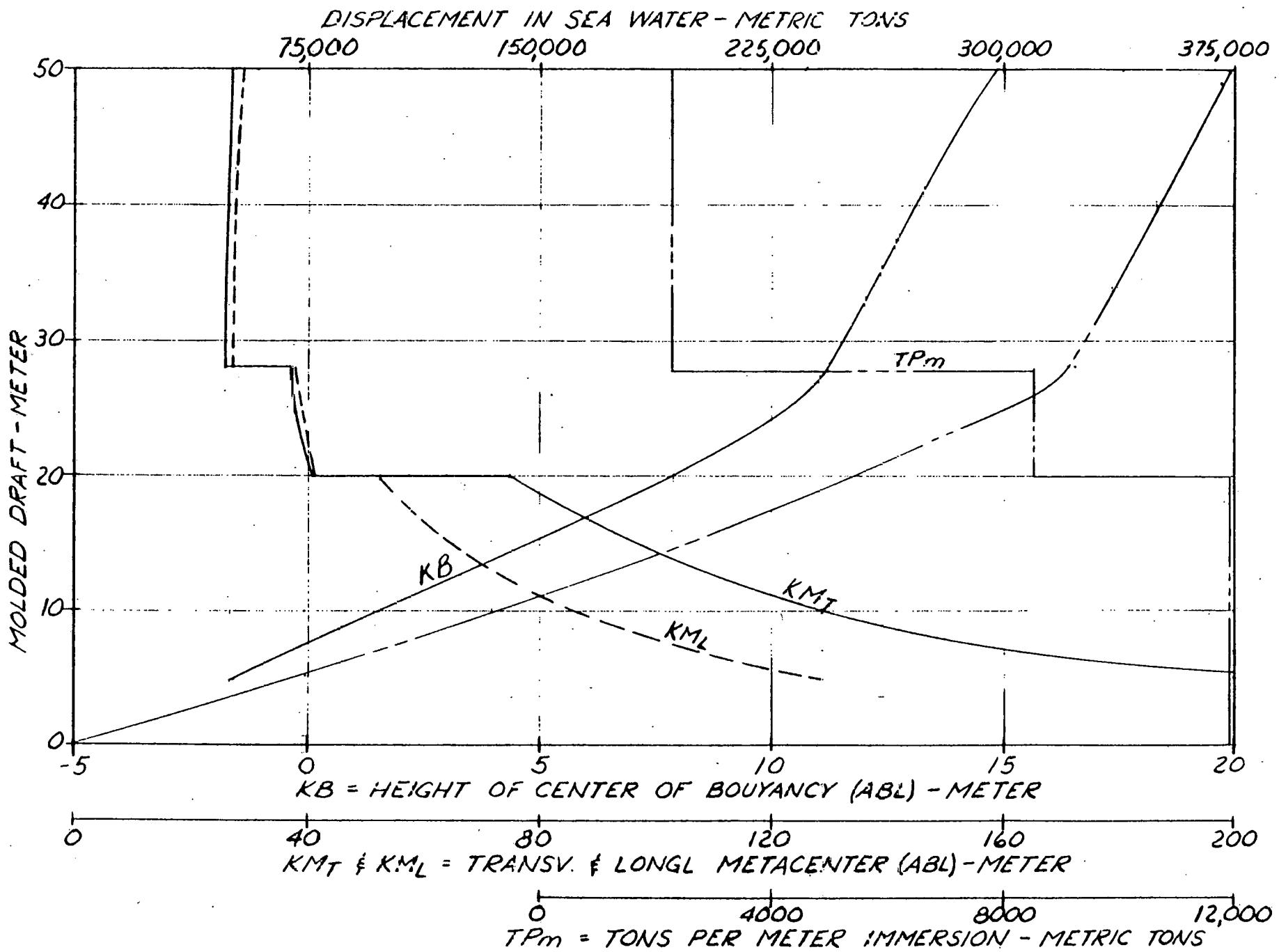
Fig. 2-43   OTEC Semi-Submersible 100 MW(e) (Net) Curves of Form

Table 2-52

OTEC SEMI-WEIGHT SUMMARY

LSMC
WBS

0.1   OTEC PLATFORM

		Lightship Weight Metric Tons	Operating Weight Metric Tons
1.0	HULL AND STRUCTURE		
1.1	Shell		
1.1.1	Pontoons	18,400	18,400
1.1.2	Mid Hull	16,100	16,100
1.1.3	Columns	10,700	10,700
1.2	Bulkhead		
1.2.1	Pontoons	2,880	2,880
1.2.2	Mid Hull	520	520
1.3	Decks	3,600	3,600
1.4	Platforms	5,900	5,900
1.5	Deck House	800	800
1.6	Not Used		
1.7	Not Used		
1.8	Foundations		
1.8.1	Cold Water Pipe	2,500	2,500
1.8.2	Equipment	4,700	4,700
1.9			
1.9.1	Fixed Ballast	50,000	50,000
1.9.2	Free Flooding Ballast		97,000
		116,100	213,000

Table 2-52 (Cont.)

2.0	SEA WATER SYSTEM		
2.1	Cold Water Pipe	55,700	24,000
2.2	Cold Water Pumps (4)	700	700
2.3	Not Used		
2.4	Warm Water Pumps (4)	700	700
2.5	Water Ducts		
2.5.1	Cold Water	2,900	2,000
2.5.2	Warm Water		
		60,000	27,400
3.0	POSITION CONTROL SYSTEM		
3.1	Mooring		
3.2	Thrusters	600	600
		600	600
4.0	SUPPORT SUBSYSTEMS	3,500	3,500
5.0	OUTFIT AND FURNISHINGS	1,000	1,000
0.2	ENERGY TRANSFER SYSTEM	200	200
0.3	POWER SYSTEM (See Table 3-1)	19,600	32,300
0.4	MISCELLANEOUS		
1.0	LIQUID BALLAST		64,000
2.0	CONSUMABLES		5,000
3.0	CWP INSTALLATION CRANE	2,000	3,000
	Total	3,000	71,000
	TOTAL W/CWP	204,000	350,000
	TOTAL WITHOUT CWP	148,300MT	326,000MT

The seawater system consists of the cold water intake pipe (CWP), cold water discharge pipe, warm water intake and discharge systems, salt water plenums, piping, pumps, and valves.

The CWP conducts water up from 1,000 m depth to the cold water intake plenum, located in the center of the vessel and extending across between the wing wall in the central hull. The cold water flows from this amply vented plenum to wing tanks, and then through butterfly valves into the saltwater pumps. After passing through the pumps and condensers, the cold water exits through another valve into the opposite wing tank. It then flows into the cold water discharge plenum, located directly below the intake plenum, and out through the cold water discharge pipe. The discharge pipe consists of a 24-m sleeve extending to a depth of 100 m around the cold water inlet pipe. This sleeve can be structurally integrated with the inlet pipe, and provides insulation between the cold inlet water and the surrounding warm surface water.

The warm water intake is provided through the sides of the 13-in. columns into plenums located centrally in the pontoons. The warm water pumps take suction from these plenums, pump the water through the evaporators and down through the ends of the pontoons. The warm water discharges from the hull at a depth of 40 meters. This distribution system eliminates the need for internal saltwater pipes.

The Semisubmersible will be held on location by a fixed mooring system. This system will limit excursion to acceptable limits as dictated by the electrical transmission cable requirements. Heading control will be accomplished by use of the thrusters located at the ends of the pontoons, possibly combined with selective manipulation of mooring line lengths. The goals of heading control will be to minimize environmental forces, minimize adverse motions, and provide warm water intake from an optimum direction with respect to current flow.

The electrical power transmission equipment is located on the upper level of the mid hull fwd of the CWP well and above the SW pumps. The power cables will transit through the hull from a common junction box. The headroom in the space is limited; however, it can be increased with a resultant penalty in hull displacement.

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The power system arrangement in the OTEC Semi results in long ammonia piping runs. The ammonia is vaporized in the evaporators located in the pontoons of the vessel. The vapor passes up through the demisters which are in the corner columns, and then down the columns and into the upper level of the mid hull where the turbo-generators are located. The turbogenerators are mounted directly above the condenser, and the liquid ammonia is piped out the bottom of the condenser back to the evaporators. The Semi has 530m of ammonia vapor piping and 530m of ammonia liquid piping. The ammonia storage tanks are located in the pontoon adjacent to the evaporators, and the inert gas storage tanks are on the lower level of the mid hull below the aft condensers.

2.4.3.3 Constructability.

(a) Facility Requirements

A single drydock 267 × 92 m (874.5 × 300 ft) can be constructed from the two 22-ft draft docks at General Dynamics, Quincy Division, shipyard. This is of sufficient size in which to build the central 80 × 80 m hull section.

The hull pontoons, 152 × 20 m (433 × 66 ft) each, can be built within numerous U.S. facilities. For modular assembly of the complete lower hull, a shoreside water depth of 5.5 m (18 ft) is required.

A new drydock capable of containing the 132 × 120 m Semi would require a draft of 7.8 m (25.5 ft).

A barge platform capable of supporting the Semi, including equipment and outfitting, would be 168 × 137 m (550 × 450 ft) with a draft of 21 ft at launch. The Semi draft after sinking the barges is 25.5 ft. Barge height is 25 ft. So a total shoreside water depth of 50.5 ft is required.

(b) Construction Methods

There are three construction methods presented for the Semi. These methods are described below. Option I is illustrated in Fig. 2-44. A summary of the percent of construction completed in each phase is presented in Table 2-53.

CONSTRUCTION ~ SECTIONS ~ EXISTING DRY DOCK

DRY DOCK (DEPTH = 22')

The 152 x 20 m hull contours including the power plant auxiliary machinery and the central hull section are built in the enlarged General Dynamics, Quincy Div, dock made by removing the separating wall resulting in a 91.5 m width. Power plant and auxiliary machinery components are installed. Drafts for the three sections are all 5.5 m ('18')

Hull Pontoons Existing Wall Central Hull

5.5 m
80 m   91 m
132 m   80 m
267 m
5.5 m

FLOAT OUT

SHORE SITE (DEPTH = 30')

After float out the sections are ballasted for vertical alignment and joined together at a shore site

The columns and enclosed equipment are erected on board using shore or barge cranes. The upper deck is installed in sections.
Draft: 7.8 m (25.5)

SHELTERED WATER (DEPTH = 80')

Install crane, concrete and complete outfitting.
Draft: 13.4 m ('44')

DEEP WATER (DEPTH = 4000')

Install CWP

CWP

Fig. 2-44 Semisubmersible 100-MW(e) (Net) Steel

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Table 2-53

SUMMARY OF CONSTRUCTION METHODS — SEMI

		Modular Construction		Single Unit Construction	On-Barge Construction
		Option I	Option I-A	Option II	Option III
DRY DOCK	Draft Required	5.5m (18')		7.8m (25.5')	—
	Facility Required	152x20m (pontoons) Existing	80x80m (center) Enlarged existing or on-barge	120x137m (410x50') New	
	Flotation	None		None	
	Work Portion	72.7%		94.8%	
	Work Completed	72.7%		94.8%	6.4m (21')
SHORE SITE	Draft Required	7.8m (25.5')			120x137m (410x450') Barge
	Flotation	None			
	Work Portion	21%			94.8%
	Work Completed	93.7%			94.8%
SHELTERED WATER	Draft Required	13.4m (44')		13.4m (44')	13.4m (44')
	Flotation	None		None	Barge
	Work Portion	6.3%		5.2%	5.2%
	Work Completed	100%*		100%*	100%*

* Excluding mobilization — CWP installation, crane installation and removal, towing.

(1) Option I – Construction in sections in existing drydocks.

   The 152 × 20 m hull pontoons are built in existing docks of 22 ft depth, including the power plant and auxiliary machinery. The 80 × 80 central hull section is built in the enlarged General Dynamics, Quincy Div., dock made by removing the separating wall resulting in a 91.5-m width. Power plant and auxiliary machinery components are installed. Drafts for the three sections are all 18 ft. After float-out, the sections are ballasted for vertical alignment and joined together in shallow sheltered water. The columns and enclosed equipment are erected on-board using shore or barge cranes and the upper deck installed in sections. The crane is installed and outfitting completed. Draft is 44 ft. In deep water, the CWP is installed.

(2) Option I-A – Center section constructed on a barge.

   This varies from option I in that the center hull section is constructed on a 84 × 84 m barge which is sunk to launch the hull. This eliminates the need to construct or enlarge docking facilities.

(3) Option II – Construction in a new dock.

   A new dock 125 × 137 m (410 × 450 ft) 30 ft deep is built in which to construct the entire Semi. The structure, power plant, and auxiliary machinery are installed. The draft is 25.5 ft. After float-out, in shallow water, the outfitting is completed and crane installed.

   In deep water the CWP is installed.

(4) Option III – Construction on barge.

   A large barge platform 125 × 137 m (440 × 450 ft) is assembled from sections and the entire Semi is constructed on top. The barge draft is 6.4 m (21 ft) with a Semi weight of 95,000 MT and barge weight of 20,000 MT at launch. The Semi is launched by sinking the barge.

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2.4.3.4 Operability.

(a) Maintenance

All power system, seawater system, electrical transmission equipment, and vessel service systems are accessible from within the hull of the Semi making on-site maintenance and repair relatively easy. On-board, workshops will handle minor repair items, and there is sufficient space to perform major equipment overhauls in the mid hull. Equipment removal while at operating draft, is limited to access through the corner columns or through the 4 m-diam. elevator shafts within the CWP well. The heat exchangers can be retubed in place. If removal is required, the Semi must deballast to expose mid-hull to remove the condenser. The evaporators can be removed through the corner columns without surfacing, allowing operation of the other modules.

(b) Operation

The Semi is similar to the Ship and Spar when in operation. All the work spaces are within a pressure hull like the Spar, but access from the workspaces to the main deck is much better on the Semi than the Spar though not as convenient as the Ship. The ammonia storage tanks are not isolated on the Semi which makes the gas detection and safety precautions related to ammonia leaks much more important on the Semi than either the Spar or Ship. The accommodations on the Semi should provide the best separation from machinery operation noise and vibration among the three vessels.

(c) Performance

(1) Intact Stability

The vessel is designed to satisfy the requirements of the American Bureau of Shipping. ABS measures intact stability by the ability of the vessel to withstand the overturning forces of a severe wind and accompanying waves.

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A measure of the stability of the intact vessel is a comparison between the overturning energy created by wind and waves and the righting energy created by the heeled vessel. The amount by which the righting energy exceeds the overturning energy up to the limiting angle is a measure of the vessel's ability to resist capsizing or downflooding. The ABS rules require that the area under the righting moment curve be at least 30% greater than the area under the heeling moment curve up to some limiting angle. The heeling moment curve used is that of a 51.5 m/sec (100 knots) wind. The limiting angle is that corresponding to either the second intersection of the two curves, beyond which the overturning moment exceeds the righting moment, or the occurence of downflooding, whichever is less.

The intact stability of the vessel has been evaluated for three conditions:

- Light draft (in transit)
- Operating draft (40 m)
- Operating mode and CWP breaks off

For each case the KG value was calculated, and for each case the area ratio between the righting moment and the heeling moment curves was greater than 1.3. The vessel has sufficient stability in the intact condition to withstand anticipated envrionmental loads to a degree established as acceptable by ABS.

(2) Damaged Stability

Damaged stability calculations are performed to assure that the vessel will survive flooding of certain spaces due to damage without capsizing or sinking or flooding into additional spaces. The extent of damage which a vessel should be able to tolerate and the environment loads which it should be able to resist are established in the ABS Rules.

This assumes that damage can occur at exposed positions of column located on the periphery of the vessel. The vertical range in which

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damage may occur extends from 1.5 m above the waterline to 1.5 m
below. The vertical extent of damage is assumed to be 3.0 m, occurring
anywhere within the assumed vertical range. The horizontal extent is
assumed to be 45 deg and the assumed depth of penetration is 1.5 m.
Therefore, if a horizontal flat is within the vertical range of damage,
it must be assumed damaged. Also, interior bulkheads must be located
inboard of the assumed depth of damage if they are to be assumed intact.

The overturning energy of wind and wave is assumed to act upon the
damaged vessel, adding a heeling moment to that caused by the flooding
water. The wind heeling moment, computed in the same manner as for
the intact stability, is that created by a 25.8 m/sec (50 knots) wind. The
ABS Rules require that the flooded vessel have sufficient stability to
sustain the heeling energy of the wind without capsizing or heeling over
to an angle at which down flooding can occur.

The Semi-submersible configuration in this study is such that the inner
columns are 2m away from the outer column shell at operating draft,
and the double skin on lower hull are at least 2m spaced. The amount
of flooded water would not cause severe heeling moment. The vessel
has sufficient stability in the damaged condition to withstand anticipated
environmental loads to a degree established as acceptable by ABS.

(3)   The amplitudes of the significant motions of the 100 MW(e) semi-submersible
        and the loads in the cold water pipe are presented in Table 2-54.

2.4.3.5 Risks. Cost and schedule associated with semi-submersible construction
is probably the only serious platform risk. Even the 100 MW(e) plant cannot be con-
structed without modularization in the GD Quincy graving dock. This implies the
employment of construction techniques not presently completely predictable although
feasibility appears highly probable.

LOCKHEED MISSILES & SPACE COMPANY, INC.

Table 2-54

CALCULATED SEAWAY RESPONSE FOR SEMI PLATFORM
IN HEAD AND BEAM SEAS, CONCRETE CWP,
$E = 0.3 \times 10^6$ PSI, 10^9 LB-FT/RADIAN
CWP ATTACHMENT STIFFNESS

Response	Units	Significant Amplitude for Significant Wave Height			
		20 ft	35.9 ft	45.8 ft	58.1 ft
HEAD SEAS					
Surge	ft	1.2	4.4	6.6	11.4
Heave	ft	1.0	3.9	6.2	11.5
Pitch	deg	0.8	1.9	2.6	3.7
Max. Acceleration	ft/sec^2	1.1	2.3	2.9	3.6
CWP Rotation	deg	1.0	2.7	3.7	5.2
Max. Bending Moment	lb-ft	1.38×10^8	4.26×10^8	5.96×10^8	8.13×10^8
Max. Bending Stress	psi	2.01×10^2	6.21×10^2	8.69×10^2	1.19×10^3
Max. Shear Force	lb	6.02×10^5	1.73×10^6	2.44×10^6	3.35×10^6
BEAM SEAS					
Sway	ft	0.8	2.8	4.4	8.1
Heave	ft	1.0	4.5	7.1	12.9
Roll	deg	0.7	1.9	2.6	3.5
Max. Acceleration	ft/sec^2	0.8	1.7	2.3	2.9
CWP Rotation	deg	1.0	2.4	3.3	4.6
Max. Bending Moment	lb-ft	9.11×10^7	2.67×10^8	3.76×10^8	5.16×10^8
Max. Bending Stress	psi	1.33×10^2	3.90×10^2	5.48×10^2	7.53×10^2
Max. Shear Force	lb	5.28×10^5	1.29×10^6	1.75×10^6	2.30×10^6

2.4.3.6 Costs.

Construction Cost — Semisubmersible

The estimated costs to construct the OTEC semisubmersible in an existing facility, assuming no draft, width, or length limitations are shown in Table 2-55. The total cost, $51M, is the base cost used in estimating the cost to build the Semi when considering construction facility limitations.

Using cost factors discussed in Section 2.4.1 and the percent of construction completed for each phase as shown in Table 2-53, a cost for each construction option was developed. A summary of these costs is shown in Table 2-56.

Mobilization Costs — Semisubmersible

Since all construction of the OTEC Semi is planned to be completed within shipyard and shallow water areas, no additional mobilization costs above those mentioned in Section 2.4.1 need be considered.

Mobilization costs — Semi: $40 to 96 million

The construction sequence from then follows that of Option II.

Table 2-55

PLATFORM CONSTRUCTION COSTS – SEMI

		$/MT	MT	COST x10^6
1.0	HULL AND STRUCTURE			
	1.1 Shell			
	1.1.1 Pontoon	3,100	18,400	57.0
	1.1.2 Mid Hull	3,100	16,100	49.9
	1.1.3 Columns	4,300	10,700	46.0
	1.2 Bulkheads			
	1.2.1 Pontoons	3,100	2,880	8.9
	1.2.2 Mid Hull	3,100	520	1.6
	1.3 Deck	3,100	3,600	11.2
	1.4 Platform	2,600	5,900	15.3
	1.5 Deck House	2,600	800	2.1
	1.6 Not Used			
	1.7 Not Used			
	1.8 Foundations			
	1.8.1 CWP	3,100	2,500	7.7
	1.8.2 Equipment	3,100	4,700	14.6
	1.9 Permanent Ballast	115	50,000	5.7
			116,100	220.0
2.0	NOT USED			
3.0	Position Control System			
	3.1 Not Used			
	3.2 Dynamic - Azimuthing Thrusters			7.0
4.0	Support Subsystem			
	4.1 Cathodic Protectors/Coating			9.9
	4.2 Machinery and related piping			3.0
	• Elevators			
	• Deck Cranes			
	• Diesel Generators (Quarters)			

Table 2-55 (Cont.)

- Emergency Generators (Quarters)
- Hoists, Tuggers, Forklifts
- Compressed air system

4.3 Hull Piping Systems/w Machinery   17.0

- Ballast
- Bilge
- De-Ballast Vent
- Sonndry
- Engine Cooling
- Compressed Air
- Lube Oil
- Fuel Oil
- Fresh Water

4.4 HVAC   11.7

4.5 Safety Equipment   1.0

- Fire Protection
- Life Boats
- Life Rafts

4.6 Electrical Work (Misc.)   1.2

4.7 Vessel Management   3.6

4.8 Accomodation   2.5
4.9 Workshops (Misc.)   1.0

4.10 Radio and Communications   0.2

TOTAL   51.1

5.0 INSTALLATION OF OWNER
FURNISHED EQUIPMENT   500   26,000   13.0

- DACS
- Energy Transfer System
- Power System
- Seawater System
- Mooring System
- 3000MT Gantry Crane

TOTAL PLATFORM COST $291,100,000

Table 2-56

CONSTRUCTION METHOD COSTS – SEMISUBMERSIBLE

Construction Location	Work Description	Option I			Option I-A			Option II			Option III		
		Weight	Unit Cost	Cost	Weight	Unit Cost	Cost	Weight	Unit Cost	Cost	Weight	Unit Cost	Cost
DRY DOCK (Cost Factor) = 1	Structure Equip. Instl.	Modular			Modular			66,100 26,000	3,240 500	214.2 13			
SHORE SITE (Cost Factor) = 1.25	Structure Equip. Instl.	66,100 26,000	3,240 500	267.7 16.3	66,100 26,000	3,240 500	267.7 16.3				66,100 26,000	3,240 500	267.7 16.3
SHALLOW WATER (Cost Factor) = 2	Structure Equip. Inst. Concrete Ballast	50,000	115	11.5	50,000	115	11.5	50,000	115	11.5	50,000	115	11.5
ON-SITE (Cost Factor) = 3	Structure Equip. Instl. Concrete Ballast												
Subtotal				295.5			295.5			238.7			295.5
Support Systems and DP Systems				58.1			58.1			58.1			58.1
Total				353.6			353.6			296.8			353.6
	Units	mt	$/mt	$ million	mt	$/mt	$ million	mt	$/mt	$ million	mt	$/mt	$ million

2.4.4 Tuned Sphere Configuration

2.4.4.1 General Description. The 100-MW(e) Tuned Sphere configuration is presented in Fig. 2-45; 200-MW(e) and 500-MW(e) configurations are presented in numerical form. Major sizing and cost data (see Table 2-57) and general arrangements are shown in keeping with the preconceptual nature of the present phase of the Study.

Reference to Fig. 2-45 reveals that cold water is drawn into each condenser from an individualized cold water trunk (canal or plenum) of relatively large cross section leading radially from the cold water pipe well. This trunk is thermally insulated from the warm water by the warm water gallery deck (0.6-m thick concrete) which forms the top clusre of the cold water trunk. Note also that turning vanes are assumed in each heat exchanger to effect flow to and from tube bundles. The 500-MW(e) plant configures cold water plumbing differently from the 100 and 200 MW(e) plants in that each condenser draws cold water from the cold water pipe well for direct axial flow through the condenser. Cold water discharge is vectored down 10 deg below the horizontal in each platform; discharge depths are 42, 48, and 52 m, respectively, for the baseline 100-MW(e), 200-MW(e), and 500-MW(e) platforms. Warm water exhaust is in each instance vertically down, exiting the vessel near the keel.

Cold water discharge on the baseline configures platforms (horizontally mounted heat exchangers) differs markedly from the off-baseline configurations. In the latter instances, all cold water discharge is vertically down in the vicinity of the cold water pipe entry to the vessel, radially inboard of the vertically discharged warm water exhaust. Plumbing runs in the latter instance are shorter and without significant "turn" loses. Less posential for thermal "fouling" is presented when considered vis a vis the baseline platforms. Off-baseline configurations for which Tuned Sphere arrangement drawings were prepared include:

- 100 MW(e) (vertical shell/tube heat exchangers) as comprised by four 25-MW(e) (net) modules of these characteristics:
  a. One 25-MW(c) (nct) module
  b. Two 12.5-MW(e) (net) submodules
  c. Three 8-MW(e) (net) submodules
  d. Five 5.0-MW(e) (net) submodules

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HEAT EXCHANGER LIFTING GEAR
SPACE. DECK AREA WITHIN
COFFERDAM REMOVABLE.
COFFERDAM PORTABLE &
FITTED AS REQ'D

NOTE: ALL MAIN CONVERTERS
SWITCHGEARS, ETC AND
TRANSFORMERS LOCATED
IN SUPERSTRUCTURE

EL 105.0 M

EL 94.5 M

EL 88.4 METERS

EL 81 METER

0.8D = 73.15 METER
OPERATING DRAFT

EL 61 METER

0.5D = 45.73 M

ELEV'N 0

SUPERSTRUCTURE

STABILITY COLUMN
WARM WATER
GALLERY

WARM WTR
INLET

COLD WATER

WARM WTR
PUMP

COLD WATER
INLET

COLD WTR
PUMP

GATE
VALVE
(TYP)

VOID W.T.

VOID W.T.

TURBO-GENR

DEMISTER
5 PER EVAP'R

EVAPORATUR

EVAP'R

BALLAST TKS

RUBBER
BELLOWS
SEAL

COLD WATER
PIPE

INBOARD PROFILE

COLD WATER
TRUNK FROM
COLD WATER WELL

WARM WATER
INLET

SHELL RADIUS
AT SECTION B-B

PUMP

PUMP
FOR CONDR'

VOID W.T.

PUMP

SHELL RADIUS
AT SECTION A-A

CONDENSER

COLD WATER
EXHAUST

EVAPORATOR

EVAP'R

WARM WATER
EXHAUST

WARM WATER
EXHAUST

SECTION B-B

SECTION A-A

1.) REMARKS: THE FOLLOWING ARE NOT SHOWN
   a.) REFLUX PUMP & PIPING SYSTEM
   b.) MIST EXTRACTOR PUMP & PIPING
   c.) NH3 CONDENSATE PUMP & PIPING
2.) ALL PROJECTIONS ARE TRUE PROJECTIONS
   MEASURED FROM WELL C.L OR BHD.
3.) ONE QUADRANT SHOWN, OTHERS SIMILAR
4.) OTHER DECKS & FLATS NOT SHOWN
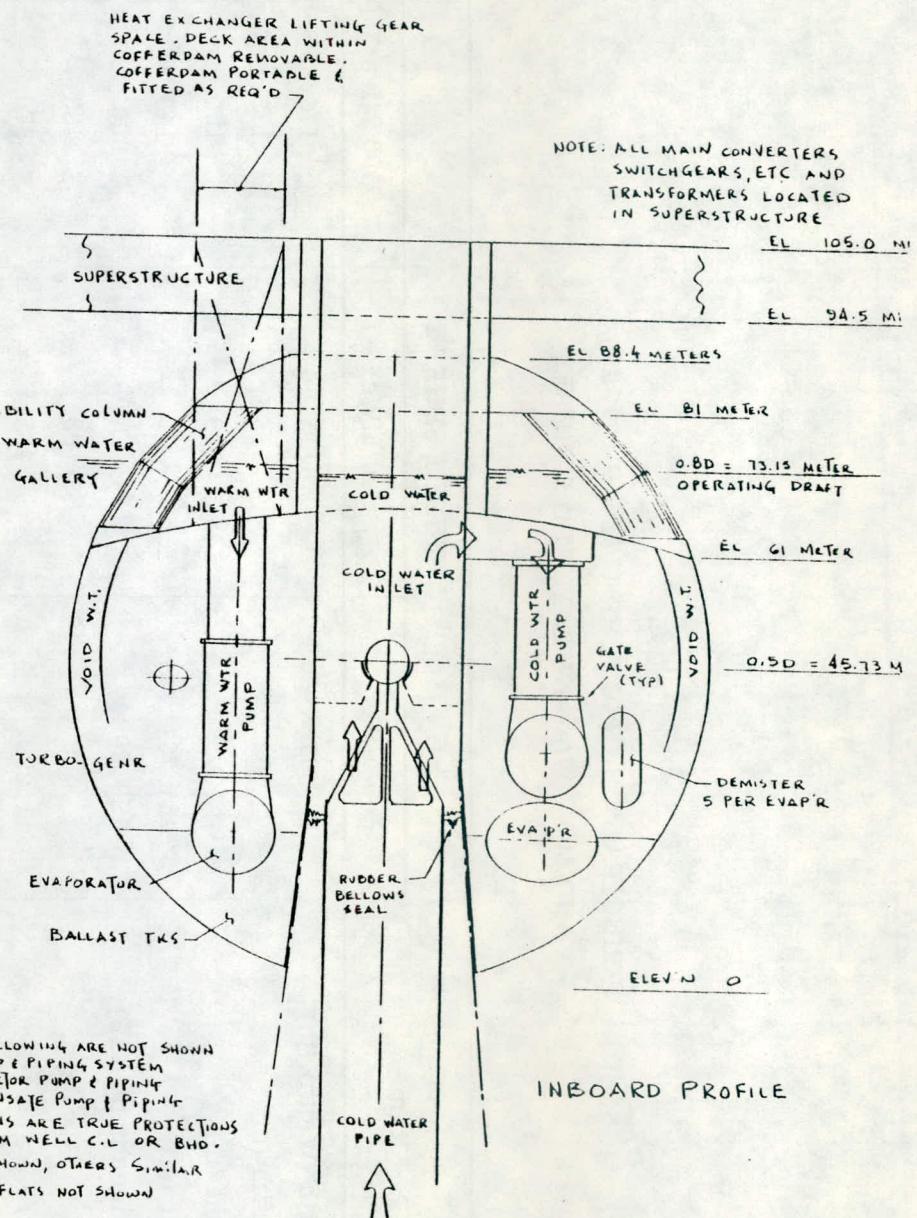
Fig. 2-45 100-MW(e) Baseline Tuned Sphere OTEC Platform

Table 2-57

PRINCIPAL CHARACTERISTICS OF 100, 200
AND 500 MW(e) (NET) TUNED SPHERES

Item	TUNED SPHERE		
	100 MWe	200 MWe*	500 MWe*
Length (Width) (m)	91	115	175
Breadth (m)	91	115	175
Height (m)	105	129	185
Draft (m)	73	92	140
Displacement (MT)	129,000	249,000	1,000,000
Cost ($\times 10^{-6}$)	$ 129	$ 93	$ 435
Cost/KWe	1,290	$ 465	$ 870

*Concrete

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The following comments appear pertinent. The smallest baseline configuration analyzed was the 100-MW(e), horizontal shell/tube heat exchanger, four 25-MW(e) net power module, design. The smallest Tuned Sphere platform into which this could be configures was of 91.44 m diam and is consistent with the off-baseline designs. Evidence is given that the 100-MW(e) baseline platform will also house a 125-MW(e) power plant provided use is made of vertically mounted heat exchangers rather than horizontally mounted ones.

In the Tuned Sphere platform this makes a strong argument for use of a power plant characterized by vertically mounted heat exchangers. An attempt to house six 25-MW(e) modules in a 91.44-m hull failed. It is inferred from 125-MW(e) and 150-MW(e) off baseline studies that the smallest Tuned Sphere hull that will accommodate an off baseline 100-MW(e) power plant is of 84 m diam. The cost savings which would be realized have not been computed. Much versatility associated with the 91.44-m hull, however, would be sacrificed in adoption of an 84-m hull design.

Table 2-58 presents derived hydrostatics data for 100, 200, and 500-MW(e) platforms at operating draft.

Table 2-58

HYDROSTATICS DATA

Platform	Displacement (LT)	Meters					
		Draft	KB	BM	KM	KG	GM
100 MW(e)	282,161	73.2	37.1	1.31	38.4	36.3	2.13
200 MW(e)	580,429	92	50.2	3.17	53.3	51.2	2.13
500 MW(e)	1,933,130	140	72.1	1.92	24.0	71.9	2.13

A summary of the sizing data for the 100-MW(e) configuration is furnished in Table 2-59.

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Table 2-59

PRINCIPAL FEATURES – TUNED SPHERE

ITEM	DESCRIPTION
Displacement (Operating Draft)	282,161 LT
Displacement (System dry, w/o ballast)	137,917
Diameter	91.44 M
Operating Draft	73.15 M
Towing Draft	46.48 M
Ballast	38,312 (Liquid) LT
	75,083 (Solid) LT
Material of Construction (Shell, pillars, major decks, vertical bulkheads & CWP well)	Concrete
Clear Superstructure Deck Area	1,821 M^2
Evaporators	Horizontal
Evaporator Protection	Trash racks between columns; screened inlets
Warm Water	Inlet 3 - 12 M below surface; Exit 56 to 66 M below surface
Condensers	Horizontal
Cold Water	Exits 10° below horizontal at 42 meter depth
KG (Operating Draft)	36.3 M
KB (Operating Draft)	37.1 M
GM (Operating Draft)	2.13 M
Tons per Inch Imersion (Operating Draft)	23.1 LT
Tons per Inch Imersion (Towing Draft)	161.7 LT
Moment to Trim One Inch (Operating Draft)	337 LT/in.
Moment to Trim One Inch (Towing Draft)	3,149 LT/in.
Buoyancy Columns, No.	16
Buoyancy Column Diameter	7.62 M
CWP Length	1,000 M
CWP Diameter (I.D.)	16.2 M
Roll Period (w/o allowance for entrained water)	39.6 seconds
Heave Period (w/o allowance for entrained water)	35.9 seconds
Warm Water Gallery	Depth, nominal 12 M (but varied by ballast control for most efficient plant operation)

2.4.4.2 Design Features.

The following comments refer to Fig. 2-45. Depicted is a 91.44 m-diam. platform housing four 25-MW(e) power plant modules. The platform operates at a keel depth of 73.2 m (draft/diameter ratio = 0.8). Sixteen 7.6-m-diam. columns plus a cofferdamed CWP vent at the vessel centerline define the waterplane area. The 16 columns and the deck at the 61-m level define the warm water gallery; vertical between-column trash racks and screens over the warm water inlets at the 61-m level are the means for preventing evaporator fouling by marine life. The warm water gallery is shown here as 12 m deep; this will accommodate a 25-m wave without uncovering the warm water inlet (refined motion analyses may well show the Tuned Sphere platform operable in 25-m waves). To operate by skimming warm water from only the warmest water layer, the platform would off-load ballast to reach the desired gallery water

depth (277 ton/ft for draft change in the operating range). Alternatively, it is conceivable that the warm water inlet diffuser would be extensible and adjusted mechanically vertically to draw water at the preferred layer depth; platform draft would in this instance remain constant.

The 61-m-level deck is provided soft patches for access to heat exchangers and other major equipments. It is anticipated the soft patch area would be cofferdamed to avoid ingestion of seas when the soft patches are penetrated; this would provide access when only a portion of the power plant is shut down. Controlled off-center de-ballasting would maintain trim when major components are removed for reconditioning at an off-center location. The CWP is shown suspended at the platform c.g.; it is provided a 7-deg deflection range before it will contact the platform hull. Damage control measures are taken which will limit listing to that degree, thereby avoiding loading of the CWP from collision flooding, etc. Motion excursions in pitch/roll and surge are such on this platform that these also will not cause contact. (The ball joint suspension has not been designed; the platform is believed to accommodate readily other CWP suspension configurations.)

A concrete hull is the basis of design, hydrostatic pressure on this hull form assuring a compression structure ideal for this structural material. Construction in an excavated pit cofferdamed from adjacent deep water is expected; subsequent construction stages would occur in near offshore regions. Inspection and maintenance of the spherical shaped hull will be facilitated by its shape. It will prove feasible to construct a blister type auxiliary compartment whose curvature adapts to that of the hull and makes a pneumatic seal therewith; this could be manned and drawn over the hull providing shirt-sleeve environment access for the closest of inspections or the most complex of large area repair operations.

Platform list stiffness readily accommodates lifting of 200 LT loads over the side at operating draft; this will satisfy all routine servicing requirements. To replace a 2031 LT dry weight horizontal evaporator or condenser the platform would be de-ballasted to maintain trim, and the heavy duty crane placed in operation. To install

the CWP, the platform would deballast to the 61-m waterline where a list stiffness of 2490 LT/in. is obtained. This means off-loading 11,500 LT of 44,557 LT of liquid ballast.

To limit flooding due to collision, a collision bulkhead is provided to the 39.6-m level; at platform operating draft of 73.2 m this protects the platform against vessels having drafts to 110 ft. Damage to two buoyancy columns (of 16) results in a draft increase of only 1.2 m and developing of a 5-deg list.

Emergency power, startup, standby, and normal service electrical equipments and watch stations require a total of 2718 cu m (6 m height by 453 sq m deck area). A total of 1575 cu m of this is made available in the 'tween decks volume at the 81 m to 88 cu m level. The balance is considered more appropriately positioned 286 cu m on platform decks in each power module quadrant.

The simplest mooring system would be a single-point mooring with a scope of 1.5 to 2. However, it becomes obvious that a current direction change or a wind change would very soon tangle (foul) the mooring line and cold water pipe; consideration of multiple leg moors followed. A two-leg system provides the necessary restraint to prevent the fouling of the cold water pipe and a mooring leg. However, each leg must be as "strong" as a single point moor, since current and wind may be in line with the two anchors. There is no redundancy; hence the failure of one moor will permit the cold water pipe to foul, either with the failed moor or the good moor. A similar analysis may be made for a three-leg moor, only it is 1/3 more expensive than a two-leg moor in materials and emplacement. A four-leg moor does offer advantages; each leg need carry only half the mooring load and in event of a failed moor the cold water pipe will not foul with a good leg. After consideration of the actual mooring loads to be encountered, a two-leg moor was tentatively selected for the Tuned Sphere configuration studies.

Examination of 100-yr return cycle storms at each candidate site revealed the Puerto Rico site as potentially developing the greatest mooring loads; these were 662 LT (162 wind, 503 current with wave drift force not computer) as compared to the New Orleans site total of 599 LT. An L. Jusne oil quality rig 4-3/4-in. chain designed with a 1.89

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safety factor, was selected. Mooring in 4000 ft of water with a 2:1 scope results in vertical loads on the anchor and platform of 56 LT and 755 LT, respectively. Chain slope at the sea bed is 5 deg. As noted, a two-leg moor was assumed.

2.4.3.3 Constructability.

(a) Facility Requirements

Construction site studies have focused on the requirement for deep water relatively close to shore, with a sloping underwater contour that facilitates a two to four stage construction/outfitting process. Two potential sites are in the Gulf Coast/Caribbean area. The first of these in in the region at the head of the DeSoto Canyon i.e., along the Florida coast, from Pensacola east to Freeport. The 10-fathom line is frequently within 1 mi of the coast, the 30 fathom line at 15 to 18 mi. Three-hundred ft of water can be reached at 20 mi. Bottom conditions would appear to facilitate necessary local dredging.

The western end of Puerto Rico, in the vicinity of Mayaguez (population proper in excess of 70,000), also appears attractive. Evidence of considerable dredging would indicate bottom conditions not unfavorable to this. Seventy ft of water is found readily within 1 mi. of the shoreline, 200 ft within 2 mi. As will be seen, the candiate operating site off Puerto Rico is significantly the most tolerant of the state-of-the-art in CWP technology, i.e., reliable long-life CWPs can be forecasted here with the highest confidence factor. Life-cycle costs will be reduced by selection of the Puerto Rico operating site; mobilization costs may be similarly affected by selection of a Puerto Rican construction site.

(b) Construction Methods

The methods investigated for the construction of the OTEC Tuned Sphere were based on the previous data obtained for the construction of Tuned Sphere concrete drilling platforms, and not any one of the methods, except as shown below, was considered

to be suitable and economical for use in construction of all section of the sphere. The construction method recommended in this report is, therefore, a staged construction method utilizing several of the methods investigated. The methods investigated were:

- Conventional Cast-In-Place Construction
- Precasting of Components for Later Assembly
- Cast-In-Place Slipforming of the Vertical Bulkheads, the Cylindrical Surfaces, and Spherical Components of Sphere
- Ground Forming of the Spherical Surfaces
- Composite Steel-Concrete Construction Methods

The basic construction procedures are summarized below for the purpose of presenting an overall perspective of one of the ways in which the construction could be economically performed.

The construction method appearing to be most feasible, as a result of this study and as summarized here, was selected only after conferences with several large contracting firms capable of doing the actual construction on the sphere. These firms provided CHENCO with a very positive reaction that the specific method proposed here was practical, economical, and could be done with existing and available equipment. The method proposed basically utilizes four construction stages or phases with Phase I being completed on land adjacent to the channel used in Phase II. After completion of Phase I, the Tuned Sphere would then be moved to the channel selected. Phase III could be accomplished in the same location as Phase II, if the channel used was deep enough or could be dredged deep enough to complete Phase III. After this, the Tuned Sphere would then be towed to deep water for completion during State IV.

The sequences of construction are very similar to the sequences used on various European concrete drilling platforms and production platforms for the North Sea oil production operations. Examples of these structures are the CONDEEP types such as used in the Beryl, Brent, Frigg, and Statfjord fields; the Philips Petroleum platform used in the Ekofisk field, the ANDOC platform used in the Dunlin Field, and the SEATANK Company designs built by Sir Thomas McAlpine in Scotland.

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Phase I consists of pouring a ground formed disc pad on plug, which will be used as foundation for the erection crane and which will remain in place until the Cold Water Pipe (CWP) is being placed in Phase IV. This pad will provide a large extra ballast chamber, during subsequent construction and transport, between the three construction locations. The spherical shell (up to the 70-ft level) is then formed using the crane mounted interior face horizintal slip-form and a prepared ground surface as the outside of the sphere. The cylindrical centerwell is then slip-formed, and after this, the remainder of the sphere is formed using the form inside and a new outside hanging form, which is progressively moved around the perimeter. This is similar to the slip-forming used in California and Texas for irrigation ditches. The centerwell and upper deck for Phase I are then poured, the earth cofferdam removed, and the Tuned Sphere moved out to the adjacent channel for Phase II construction.

Phase II construction is accomplished in much the same manner as the latter stages of Phase I. Many of the components of equipment and machinery are proposed to be installed in Phase II, depending on the water depth available in the channel and the route to the deep water Phase III and IV site. In essence, as much equipment and basic shell structure as possible will be built and installed in Phase II, being only limited by the draft of the light ship shell and the channel depth. When the maximum draft is reached, at which the Tuned Sphere may be loated to Phase III and IV construction site, then Phase II will be considered complete and the Tuned Sphere moved to the third site in deep water.

Phase III is accomplished in deep water. Most of the heavy equipment will be installed with large barge mounted marine cranes and a mobile large capacity crane or cranes put aboard for use in Phase III operations. The centerwell crane will be retained for use in handling smaller components and general utility materials handling.

Phase IV involves the installation of the substructure in several pieces (at least four), which will be erected with the barge mounted marine cranes; and later, after removing

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the bottom disc pad or plug, the CWP will be installed in the centerwell. The study of the design of a self erected special centerwell crane of large capacity, which could remain aboard and lift the heavier components from barges during Phase IV, would certainly be a valid consideration for saving a substantial amount of time and marine barge crane rental. The method outlined does not appear to require any technology or equipment not available now and should be a satisfactory construction method.

2.4.4.4 Operability.

(a) Maintenance

A maintenance capsule (hemispherical blister-type with pneumatic seal shaped to mate hull spherical external radius) approximately 10 m in diam. is stored (when not in use) in the cold water well vent at approximately the 81-m elevation; see Fig. 2-45. A portable major equipment maintenance trunk/cofferdam, 12 m ID × 18 m length, is also stowed in the cold water well vent (88-m elevation) when not in use. When used, it is positioned by the heavy-duty deck crane around a warm water inlet and secured water tight to the warm water gallery deck. After de-watering its internal volume and that of the associated evaporator loop, major internal equipments are safely accessed for cleaning, inspection, or replacement. Three-quarters of the power plant remains in operation while one power module is serviced. Removal of heat exchangers requires removal of one or more stability columns, installation of a cofferdam, and removal of a soft patch on the hull. Direct vertical lift of the heat exchangers can be accomplished by this somewhat complex process.

(b) Performance

(1) Towing Resistance — Fluid imposed towrope resistance was determined for the Tuned Sphere, with and without CWP, at a velocity of 3.5 knots; these values were 1736 LT and 507 LT, respectively, at operating drafts. These are reduced to 1622 LT and 393 LT at tow draft; 35,051 and 9462 horsepower, respectively. The CWP is seen to add a horsepower requirement of 25,589 when towing at 3.5 knots at tow draft, no-wind conditions.

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It is seen that a 20-knot opposing wind adds 2334 HP to the towing requirement at tow draft. This makes required tow horsepower, enroute site without CWP, at 3.5 knots at tow draft in a 20 knot opposing wind, 11,796 horsepower.

(2) <u>Intact Stability</u> — Intact, initial stability was investigated with respect to the normal physical parameters that effect it and with respect to its affect on the motion response of the vessel. Placement of major components was as low as practicable within the hull to reduce the KG of the vessel's lightship to a minimum, while sufficient liquid ballast capacity was provided to alter the operating KG either up or down.

The gallery design had to allow sufficient transparency of structure while maintaining enough waterplane area and inertia for stability requirements at the operating draft. Additionally, the diameter of the gallery columns had to be such that positive intact stability was maintained over the entire range of draft. While the waterplane inertia value for the operating draft met minimum stability standards it was found during initial examination that GM was negative at the draft where the columns adjoin the gallery deck rim. In order to correct this deficiency the column diameters were increased giving an initial GM of 2.13 m with free surface correction at the 73.2 m operating draft.

(3) <u>Damage Stability</u> — Although the probability of damage to the main hull appears relatively low, normal considerations to damage stability were given to ensure that the vessel remained floating when in the damaged state at the upper levels.

It was felt that damage from surface vessel collision could cause the gallery columns to be flooded or destroyed. Vertical flooding is minimized by designing watertight flats within the columns, however the analysis investigated the total destruction of two columns. With the absence, or flooding of two complete columns, the vessel takes on a level sinkage of 1.25 m and immediately heels to an angle of 5 deg. Such damage can readily be compensated by deballasting and flooding opposite tanks to regain a level operating draft. The total effect to the plant and the vessel from a collision by a surface vessel having a draft of 40 ft or less would thus be minimal and would not require the shut-down of plant or evacuation of

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personnel. Similarly, the removal of complete heat exchangers or other major components could be achieved by their withdrawal vertically through the bolted dished head openings in the gallery deck, followed by either their vertical movement to the superstructure deck or their lateral movement out through the warm water gallery. In the latter case, removal of one or two buoyancy columns would be required. Installation design would provide for this. As noted above, compensating ballast rearrangement would prevent listing in the course of column and equipment removal and would preclude necessity for shut-down of other power modules.

The design shows a double skin concrete hull from the gallery level down to the 36.9 m elevation. The distance from the external shell to the inner shell is 4.6 m. It was felt that the probability of damage from collision at this level was extremely small since most surface vessels sail at drafts of 40 ft or less, particularly vessels serving the southeast and Gulf Coast areas of the United States. Large tankers would be the only surface vessel that could possibly damage the vessel below the 40-ft depth level.

Since the vessel is constructed from reinforced concrete of at least 0.75 m thickness in this area, it was felt that the absorption of energy from collision at this depth would be such that penetration into the vessel could be limited to less than 4.6 m. This philosophy is weighed against the standard U.S. Coast Guard requirement for surface vessels to maintain adequate stability after collision with a penetration depth of 1/5 the beam. Meeting such a standard would of course result in a large increase in vessel size, regardless of platform type.

The double skin structure surrounds the major machinery components from the 39.6-m depth level to the 61-m level and is sub-divided into vertical watertight segments of about 5.5 m. This degree of subdivision was chosen to allow for damage at a watertight bulkhead, thereby flooding two tanks or 11 m of perimeter. Initial heel in this condition would be limited to less than 7 deg which can be readily compensated by deballasting about 1200 tons of ballast from a lower tank directly below the damaged area.

The possibility of damage to the shell below the 36.9 m level from an external source appears extremely small. Certainly a surface vessel could not penetrate this area and it would be most unlikely for a submerged vessel to accidently collide

with a 282,000 ton charted vessel. Additionally, should penetration of the outer skin occur for some reason, cellular design of the concrete structure in this area would prohibit the entrance of water through the inner shell. For these reasons, the determination of the effects of damage in the area below the 39.6-m level was not investigated. However, if it is later proven that the probability of damage to this lower region of the sphere was greater than initially thought, then the 4.6-m, double skin structure would be extended to protect levels below the 36.9-m elevation.

(4) Motions and Loads. The motions of the platform are summarized in Table 2-60 as well as the loads in a flexible-joint, concrete cold water pipe. The motions of the Tuned Sphere are generally small and among the smallest of the several platforms. The dynamic loads in the cold water pipe are moderate. Optimizing the loads in the CWP by variations in attachment location and stiffness may improve the loads and the resulting costs for the CWP. Platform pitch motions have been shown to increase as the loads in the cwp are reduced. The overall optimum CWP/platform requires integrated power system and platform optimization.

2.4.4.5 Risks. The only serious risk associated with the Tuned Sphere is related to construction. This is largely attributable to the unique shape of this platform for the size under consideration. It is the only configuration given a "beyond the current state of the art" rating by T.Y. Lin in their evaluation of concrete construction feasibility. The 100 MW(e) plant would be marginally constructable in the GD Quincy graving dock. Any larger platforms must be modularized or constructed in specially developed facilities, barges, etc. Modularization of the sphere will require ingenuity.

2.4.4.6 Costs. Platform costs for Tuned Sphere for 100-MW(e), 200-MW(e) and 500-MW(e) outputs are presented in Table 2-61. A summary of weights and subsystem costs os presented in Table 2-62 for first units and Table 2-63 for subsequent units.

Table 2-60

CALCULATED SEAWAY RESPONSE FOR TUNED SPHERE PLATFORM
IN HEAD AND BEAM SEAS, CONCRETE CWP,
$E = 0.3 \times 10^6$ PSI, 10^9 LB-FT/RADIAN
CWP ATTACHMENT STIFFNESS

Response	Units	Significant Amplitude for Significant Wave Height			
		20 ft	35.9 ft	45.8 ft	58.1 ft
HEAD SEAS					
Surge	ft	2.0	5.7	8.2	12.6
Heave	ft	0.5	1.0	1.3	3.0
Pitch	deg	0.5	1.7	2.6	5.7
Max. Acceleration	ft/sec^2	1.0	2.2	2.9	3.9
CWP Rotation	deg	0.4	1.5	2.1	4.6
Max. Bending Moment	lb-ft	2.17×10^8	5.49×10^8	7.54×10^8	1.01×10^9
Max. Bending Stress	psi	3.16×10^2	8.01×10^2	1.10×10^3	1.47×10^3
Max. Shear Force	lb	1.30×10^6	2.98×10^6	4.06×10^6	5.48×10^6
BEAM SEAS					
Sway	ft	Same as Head Seas			
Heave	ft				
Roll	deg				
Max. Acceleration	ft/sec^2				
CWP Rotation	deg				
Max. Bending Moment	lb-ft				
Max. Bending Stress	psi				
Max. Shear Force	lb				

Table 2-61

BASELINE PLATFORM COSTS — TUNED SPHERE

Platform	Dollars, 1978
100 MWe Steel, 1st Unit	129,080,000
100 MWe Concrete, 1st Unit	58,787,000
100 MWe Concrete, Others	54,387,000
200 MWe Concrete, 1st Unit	93,231,000
500 MWe Concrete, 1st Unit	435,051,000

2.4.4.7 Mobilization Cost Estimates. Except to the degree that outfitting, mooring, rigging for power distribution ashore, and CWP installation are facilitated or encumbered by the platform design under consideration, mobilization costs for the various platform candidates will be nominally the same. Absolute (quantitative) mobilization cost estimating has not been performed for Tuned Sphere OTEC platforms. Comparative (qualitative) cost estimating can only be done by persons familiar with designs for each of the six candidate platforms. In that instance, the evaluator can rank platforms as to ease of outfitting, mooring, CWP installation, etc., with the resultant weighted rankings inferred to be a ranking of candidates as to mobilization costs. T.S.I. studies on outfitting, mooring, and CWP installation, reported in Reference 1, would indicate favorable motilization costs can be anticipated, e.g., the CWP can be installed without recourse to a 3000 ton crane barge.

2.4.4.8 Schedule. It is estimated that approximately 30 months will be required for construction of the Tuned Sphere subsequent to all engineering and facility preparation.

2.4.4.9 Summary. The Tuned Sphere point design adequately accommodates the baseline power system and the vertical heat exchangers. The vertical flow heat exchangers appear to be more readily arranged than at the horizontal flow heat exchangers. Integration with a power system should allow more efficient use of the displacement.

Table 2-62

FIRST UNIT COST ESTIMATES, FOUR PLATFORMS – TUNED SPHERE

HULL/STRUCTURE COST ELEMENT		100 MWe (Steel)		100 MWe (Concrete)		200 MWe (Concrete)		500 MWe (Concrete)	
		MT	K$	MT	K$	MT	K$	MT	
1.1	Shell & Support Structure	16,236	52,949	30,267	21,650	80,485	46,980	356,751	192,620
1.2	Hull Structural Bulkheads	5,748	17,818	13,459	16,604	6,878	12,314	107,964	108,025
1.3	Hull Decks	1,717	5,321	1,814	793	2,268	991	4,535	1,982
1.4	Hull Platform & Flats	11,716	36,321	26,275	11,482	40,513	17,704	174,254	76,149
1.5	Dock House	381	990	381	990	476	1,238	952	2,476
1.6	Special Structures	596	1,551	302	786	887	2,305	1,735	4,510
1.7	Masts, Kingposts, etc.	91	236	91	236	147	383	238	619
1.8	Foundations	2,863	8,875	8,549	3,215	15,465	5,815	98,241	36,939
1.9	Special Purpose Systems	111,645	5,017	31,759	3,031	102,336	5,501	255,061	11,731
	TOTALS	150,993	129,080	112,898	58,787	249,454	93,231	999,731	435,051

Table 2-63

COST ESTIMATES, SUBSEQUENT UNITS – TUNED SPHERE

HULL/STRUCTURE COST ELEMENT	100 MWe (Steel)		100 MWe (Concrete)		200 MWe (Concrete)		500 MWe (Concrete)	
	MT	K$	MT	K$	MT	K$	MT	K$
1.1 Shell & Support Structure	NO ESTIMATE	NO ESTIMATE	30,267	19,956	80,485	42,311	356,751	171,679
1.2 Hull Structural Bulkheads			13,459	16,035	6,878	12,110	107,964	102,892
1.3 Hull Decks			1,814	683	2,268	854	4,535	1,708
1.4 Hull Platform & Flats			26,275	9,897	40,513	15,261	174,254	65,640
1.5 Deck House			381	999	476	1,238	952	2,476
1.6 Special Structures			302	786	887	2,305	1,735	4,510
1.7 Masts, Kingposts, etc.			91	236	147	383	238	619
1.8 Foundations			8,549	2,771	15,465	5,012	98,241	31,841
1.9 Special Purpose Systems			31,759	3,031	102,336	5,501	255,061	11,731
TOTALS								

2.4.5 Submersible Configuration

2.4.5.1 General Description. The 100-MW(e) submersible configuration is presented in Fig. 2-46; 200 MW(e) and 500-MW(e) configurations are presented in numerical form. Major sizing and cost data (see Table 2-64) and general arrangements are shown in keeping with the pre-conceptual nature of the present phase of the OTEC Study. Mass properties for the three configurations are given in Tables 2-65, 2-66, and 2-67, in the order 100 MW(e), 200 MW(e), and 500 MW(e).

The OTEC plant components, their size, and proper orientation to each other was the overriding consideration in determining the arrangements and the principal dimensions of the platform. The principal dimensions were minimized to reduce construction, maintenance, and operation costs. In this preliminary stage of the design, the results of naval architecture calculations have not required that changes be made in the OTEC plant arrangements or platform principal dimensions. Double shell or approximate location of watertight one-compartment subdivision bulkheads were considered in the design of arrangements. Requirements imposed on the OTEC plant in the baseline design are identical to those presented in Section 2.4.2.1.

2.4.5.2 Design Features. The main pressure hull envelope will be constructed of higher strength steels, welded throughout. A double shell will be provided on the ends. Higher strength steels will also be used as required at the hull/CWP interface and any other critical areas. The shell will be framed circumferentially with deep web ring frames and intercostal longitudinals.

Main watertight bulkheads will be located as shown on the general arrangement drawing. Bulkhead scantlings will be designed for the hydrostatic head at the maximum submerged depth. Details of continuity and tightness of the bulkheads will be developed to provide necessary strength and watertight subdivision.
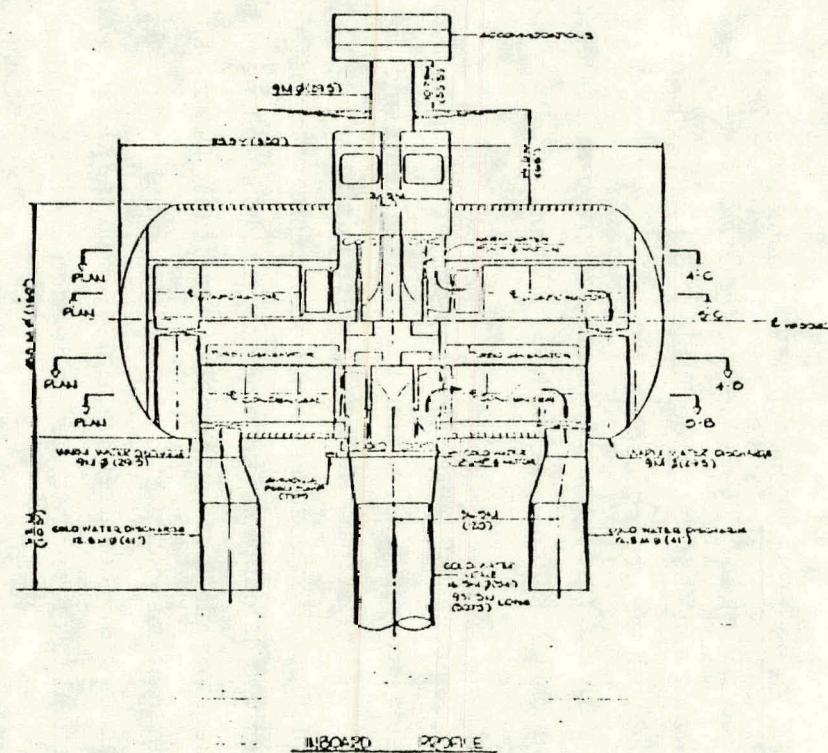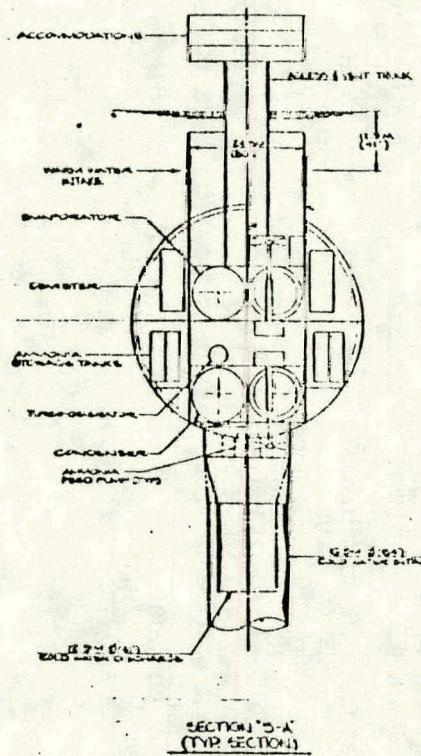
Fig. 2-46 Submersible 100 MW(e) (Net) Steel

Table 2-64

PRINCIPAL CHARACTERISTICS OF 100-,
200-, AND 500-MW(e) (NET)

Item	SUBMERSIBLE		
	100 MW(e)	200 MW(e)	500 MW(e)
Length (Width) (m)	104	195	335
Breadth (m)	49	49	119
Height (m)			
Draft (m)	69	69	69
Displacement (MT)	254,000	463,000	1,354,000
Cost ($\times 10^{-6}$)	$ 247	$ 398	$ 887
Cost/KW(e) (Net)	$ 2,470	$ 1,990	$ 1,774

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Table 2-65

MASS PROPERTIES (100-MW(e) SUBMERSIBLE)

Length 103.6 M. (340'); Diameter 48.8 M. (160').

Approximate weight estimate and prelimiarny characteristics:

	METRIC TONNES	LONG TONS
Hull Steel Weight		
Shell	26,417	26,000
Decks	3,048	3,000
Bulkheads	7,112	7,000
Superstructure	1,016	1,000
Hull Structure	37,593	37,000
Power System Foundations	12,193	12,000
Cold Water Pipe (Dry) 16.5M. I.D.	55,883	55,000
Sea Water Piping	6,096	6,000
Fixed Ballast	- 0 -	- 0 -
Power System (Dry)	32,514	32,000
Light Ship (Dry)	144,279	142,000
Power System Water (Internal)	19,305	19,000
Power System Water (External)	15,241	15,000
Power System Water (Exchangers)	7,112	7,000
Warm Water Intake Box	9,144	9,000
Variable Ballast	58,931	58,000
TOTAL WEIGHT (OPERATING)	254,012	250,000

Table 2-65 (Cont.)

	METERS	FEET
Draft to Bottom of Hull, Submerged	68.6	225
K.G. Without Ballast & CWP	-4.6	-15
K.G. With Ballast & CWP	-54.9	-180
K.B.	-2.1	-7
B.G. With Ballast & CWP	52.7	173
Radii of gyration without Ballast or CWP R_{xx}	24.4	80
R_{yy}	33.5	110
R_{zz}	38.1	125

NOTE: K is at center of Hull

Table 2-66

200 MW(e) (NET) OFF-BASELINE DESIGN

Mass Properties for 200 MWe Submersible

Length = 195.1 M. (640 ft.); Diameter = 48.8 M. (160 ft.)

	METRIC TONNES	LONG TONE
Hull Structure:		
Shell	40,642	40,000
Decks	5,080	5,000
Bulkheads	10,160	10,000
Superstructure	1,016	1,000
Hull Structure	56,899	56,000
Power System Foundations	20,321	20,000
Cold Water Pipe (Dry)	79,252	78,000
Sea Water Piping	11,177	11,000
Fixed Ballast	- 0 -	- 0 -
Power System (Dry)	65,027	64,000
Light Ship (Dry)	232,675	229,000
Power System Water (Internal)	41,658	41,000
Power System Water (External)	25,401	25,000
Power System Water (Exchangers)	14,225	14,000
Cold Water Pipe Attachment Box	20,321	20,000
Variable Ballast	129,038	127,000
TOTAL WEIGHT (OPERATING)	463,317	456,000

Draft to bottom of Hull, Submerged = 68.6 M. (225 ft.)

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Table 2-67

HULL CHARACTERISTICS (500-MW(e) SUBMERSIBLE, TWIN HULLS)

Mass Properties for 500 MWe Submersible:

Length = 335.3 M. (1100 ft.); Diameter = 45.7 M. (150 ft.) (Twin Hulls).

Approximate weight estimate and preliminary characteristics:

	METRIC TONNES	LONG TONS
Hull Structure:		
Shell	121,926	120,000
Decks	5,080	5,000
Bulkheads	20,321	20,000
Superstructure	2,032	2,000
Hull Structure	149,359	147,000
Power System Foundations	44,706	44,000
Cold Water Pipe (Dry)	124,974	123,000
Sea Water Piping	30,481	30,000
Fixed Ballast	- 0 -	- 0 -
Power System (Dry)	162,568	160,000
Light Ship (Dry)	512,088	504,000
Power System Water (Internal)	195,081	192,000
Power System Water (External)	34,332	33,000
Power System Water (Exchangers)	36,578	36,000
Cold Water Pipe Attachment Boxes	73,155	72,000
Variable Ballast	453,157	446,000
TOTAL WEIGHT (OPERATING)	1,354,391	1,333,000

Draft to bottom of Hull, Submerged 68.6 M. (225 ft.)

Strength decks will be located at four levels as shown on the general arrangement drawing and designed for the hydrostatic head at the maximum submerged draft. Deck penetrations will be compensated by insert plates of extra thickness. Platforms and flats will be provided as required to suit axuiliary machinery arrangements.

A deck house will be provided above the waterplane surface that will contain all accommodations, store spaces, communications and navigation spaces. and miscellaneous service areas. Bulkheads and decks will be steel, and all boundaries will be watertight. The house structures will be supported by the house boundaries. bulkheads, trunks and casings, and by a system of pillars, beams, and girders. The entire deck house will be supported on the submerged hull by a 9-m-diam column. This column will also be an access and ventilation trunk between the surface and the submerged hull. The above-surface deck house location was chosen to provide better habitability and more convenient air and sea access for replenishment.

Masts and kingposts will be provided as required to support the antenna arrays, aids to navigation, and ventilation systems. Service platforms, decks, and gratings will be included as required to provide access to all equipment for operation and maintenance.

Foundations for the heat exchangers, pumps, tanks, turbo-generators, and other heat equipment will be of welded steel construction throughout. Foundation girders and webs will be integrated with basic hull structure and will have long tapers in reducing to primary structure.

Adequate access will be provided in all foundations for cleaning, maintenance. and proper operation of equipment. Foundation structures will be designed to act as complete supports for all static and dynamic loads and will be suitably tuned to minimize vibrations caused by rotating machinery. A detailed finite-element structural analysis will be required for the cold water pipe foundation to insure a suitable transition between the foundation and the surrounding hull structure.

2.4.5.3 Constructability. Existing domestic construction facilities include graving docks that will accommodate lengths up to 1200 ft, breadths up to 200 ft and drafts up to 40 ft. Submerged pressure hull beam (diameter) is the one critical dimensions that will have a major impact on selection of existing facilities. The number of hulls to be constructed will also be of major importance in determining whether to adopt construction methods to existing facilities or incur the cost of a specially built construction yard.

Restricting constructability concepts to existing facilities, it is entirely within the state-of-the-art to build the pressure hull partially in a graving dock (up to drydock weight limits or float-out draft limits) and complete the hull afloat.

Shipyards with existing facilities for this type of construction include the Bethlehem-Sparrows Point Yard in Baltimore, Maryland, Sun Shipbuilding and Drydock Co. in Chester, Pa.; Ingalls Shipbuilding Corp. in Pascagoula, Miss.; and National Steel and Shipbuilding Co. in San Diego, Ca.

The construction sequence would provide for bottom shell, dished end shell, and interior decks and bulkheads to be erected in a graving dock up to a depth to be determined by the contractor. Major power system and seawater system components would be installed in timely sequence as the hull is erected. This would continue until the drydock weight limitations or float-out draft limitations were reached.

After float-out, construction of the upper portion of the shell, installation of the evaporators, and construction of the warm water system would continue at an outfitting pier or in sheltered waters, depending upon draft limitations. Preliminary weight estimates indicate that the entire hull (excluding the cold water pipe projections) could be completed in this manner within the limits of domestic facilities.

Installation of the cold water intake pipe and the cold water discharge pipes would have to be carried out afloat on-site. The installation sequence would also require that the accommodation superstructure and the supporting column for same would have to be

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fabricated ashore and installed on-site. The pressure hull would remain on the surface until the cold water pipes had been installed down through the hull. The superstructure and supporting column would then be installed, sealing the pressure hull. The hull would then be ballasted down to operating depth.

2.4.5.4 Operability. A permanent mooring system will be used to keep the platform on station and to minimize loads on the power transmission system cables. A positioning system of rotatable thrusters may be used to orient the platform so that sea currents at the surface are perpendicular to the intakes for warm water. The positioning system may also orient the platform to minimize loads on the transmission cable and cold water pipe and weather affect on crew comfort.

Because of the size of this platform and the cold water pipe hull maintenance can not be performed in a normal shipyard. For steel hulls periodic maintenance will be required at 4-yr intervals at the platform moored site. This will require cleaning, sandblasting and painting in an artifical dry environment. Underwater vehicles with devices which can scrape off large growth will be required to precede vehicles which move over the surface of the hull and form a large sealed dry space for sandblasting and painting. This will be a continual hull maintenance program so that each area of the submerged hull will be cleaned and painted very 4 yrs. At these periods ultrasonic gaugings will be taken to check for any deterioration of hull material. Cold water and warm water discharges will be made of low maintenance concrete and should not require maintenance to preserve material.

For periodic maintenance of the OTEC plant components, overhead cranes will be installed from the overhead of each deck to assist in removal and installation of large items. The arrangements of each deck will allow for removal of major components. The pressure hull will have to surface by blowing ballast and major components will be removed thru a soft patch in the pressure hull. This allows direct vertical removal of the heat exchangers. However, plant operations must be shut down completely for removal of most power system components.

Motions of the 100-MW(e) submersible and the loads in a flexible-joint, concrete cold water pipe are presented in Table 2-68. The motions are small except for roll motions in beam seas which are moderate. The dynamic loads in the CWP are small.

2.4.5.5 Risks. The submersible configuration may be easily fit into the GD Quincy graving dock for the 100-MW(e) plant and probably for plants as large as 250-MW(e). Also, the type of construction required is not new except for the large dimensions involved. Costs, schedule and feasibility are reasonably predictable and therefore constitute little risk.

The time that the platform is surfaced and open during removal of power system components requires that the hull, CWP, and the CWP/Hull attachment must be designed for some degree of severe environmental exposure. This double set of design requirements may cause the final platform design to be less efficient than it might be if it were optimized as a true submersible. This risk becomes an uncertainty in the outcome of future design efforts to yield a platform which would display the qualities present in this preliminary conceptual study. In addition, a power system which requires regular (rather than occasional) removal/replacement will cause considerable loss of power availability.

2.4.5.6 Costs. Cost estimates for the 100-MW(e), 200-MW(e), and 500-MW(e) platforms are presented in Tables 2-69, 2-70, and 2-71 respectively.

2.4.5.7 Schedule. It is estimated that 42 months will be required for the construction of the 100-MW(e) submersible.

2.4.5.8 Summary. The submersible configuration of platform provides an adequate platform for the internal baseline power system. The arrangement makes very good use of the volume of the submersible. The cylindrical structural arrangement makes this the most efficient hull design for submerged or near surface platforms. The efficiency of the submersible platform seems to be limited to arrangements that are tailored to the power system. Variations in power system developments would likely cause changes in the proportions for a submersible which could cause some loss of optimization. Smaller length vertical demisters or other types could be expected to allow even more packaging efficiency.

Table 2-68

CALCULATED SEAWAY RESPONSE FOR SUBMARINE PLATFORM
IN HEAD AND BEAM SEAS, CONCRETE CWP,
E = 0.3 × 10⁶ PSI, 10⁹ LB-FT/RADIAN
CWP ATTACHMENT STIFFNESS

Response	Units	Significant Amplitude for Significant Wave Height			
		20 ft	35.9 ft	45.8 ft	58.1 ft
HEAD SEAS					
Surge	ft	1.1	3.0	5.4	9.5
Heave	ft	1.0	3.5	5.4	9.6
Pitch	deg	0.6	1.6	2.2	3.4
Max. Acceleration	ft/sec²	0.6	1.3	1.8	2.3
CWP Rotation	deg	0.9	2.4	3.3	5.1
Max. Bending Moment	lb-ft	1.79×10^8	5.22×10^8	7.12×10^8	9.48×10^8
Max. Bending Stress	psi	2.61×10^2	7.61×10^2	1.04×10^3	1.38×10^3
Max. Shear Force	lb	8.00×10^5	2.31×10^6	3.17×10^6	4.15×10^6
BEAM SEAS					
Sway	ft	1.4	4.2	6.2	10.2
Heave	ft	1.6	4.7	6.9	11.2
Roll	deg	0.7	3.7	6.1	10.5
Max. Acceleration	ft/sec²	0.6	1.5	2.2	3.4
CWP Rotation	deg	0.8	3.7	6.2	11.0
Max. Bending Moment	lb-ft	6.03×10^7	2.41×10^8	4.03×10^8	7.60×10^8
Max. Bending Stress	psi	8.7×10	3.51×10^2	5.88×10^2	1.11×10^3
Max. Shear Force	lb	3.13×10^5	1.24×10^6	2.05×10^6	3.52×10^6

Table 2-69

100 MW(e) (NET) SUBMERSIBLE COST ESTIMATE – STEEL HULL

	ITEM	WT.	$/MT.	ECF[1]	TOTAL COST
1.	Lower Hull	15,892	$3,100	1.0	$ 49,265 x 10³
2.	Upper Hull	21,040	3,100	2.0	130,448 x 10³
3.	Power System Foundation	12,200	3,100	1.0	37,800 x 10³
4.	Superstructure and Support Structure	1,000	3,100	3.0	9,300 x 10³
5.	Accommodations	–	–	–	2,450 x 10³
6.	Discharge Pipes	1,884	3,100	3.0	17,521 x 10³
				TOTAL:	$246,784,000

NOTE: (1) Erection Complexity Factor is used to correct $/MT values for varying construction conditions. We have assigned a factor of 1.0 for erection in graving dock, 2.0 for completion afloat in sheltered water, and 3.0 for all construction required on-site.

(2) Total Cost Estimate does not include Power System costs, Sea Water System costs or Electrical Transmission System costs.

Table 2-70
200 MW(e) SUBMERSIBLE COST ESTIMATE – STEEL HULL

	ITEM	WT.	$/MT	ECF	TOTAL COST
1.	Lower Hull	29,914	$3,100	1.0	$ 92,733 x 10³
2.	Upper Hull	26,146	3,100	2.0	162,105 x 10³
3.	Power System Foundations	20,300	3,100	1.5	94,400 x 10³
4.	Superstructure & Column	1,143	3,100	3.0	10,630 x 10³
5.	Accommodations	-	-	-	2,975 x 10³
6.	Discharge Pipes	3,768	3,100	3.0	35,042 x 10³
				TOTAL:	$397,885,000

NOTE: (1) Erection Complexity Factor is used to correct $/MT values for varying construction conditions. We have assigned a factor of 1.0 for erection in graving dock, 2.0 for completion afloat in sheltered water, and 3.0 for all construction required on-site.

(2) Total Cost Estimate does not include Power System costs, Sea Water System costs or Electrical Transmission System costs.

Table 2-71

500 MW(e) SUBMERSIBLE COST ESTIMATES – STEEL HULL

ITEM	WT.	$/MT	ECF [1]	TOTAL COST
1. Lower Hull	102,830	$3,100	1.0	$318,773 x 10^3
2. Upper Hull	46,500	3,100	2.0	288,300 x 10^3
3. Power System Foundations	44,700	3,100	1.5	207,900 x 10^3
4. Superstructure & Column	2,032	3,100	3.0	18,900 x 10^3
5. Accommodations	–	–	–	3,500 x 10^3
6. Discharge Pipes	5,307	3,100	3.0	49,355 x 10^3
			TOTAL	$886,728,000

NOTE: (1) Erection Complexity Factor is used to correct $/MT values
for varying construction conditions. We have assigned a
factor of 1.0 for erection in graving dock, 2.0 for completion afloat in sheltered water, and 3.0 for all construction required on-site.

(2) Total Cost Estimate does not include Power System costs,
Sea Water System costs or Electrical Transmission System
costs.

2.4.6 Spar Configuration

2.4.6.1 General Description. The 100-MW(e) spar configuration is presented in
Fig. 2-47 and 2-48. 200-MW(e) and 500-MW(e) configurations are summarized in
the text. Major sizing data and general arrangements are shown, in keeping with the
preconceptual nature of the present phase of this OTEC Study. A summary of the key
sizing data for the three platform is presented in Table 2-72.

The size of the proposed OTEC Spar is essentially determined by size of the heat
exchangers and the sea-water pumps. Growth of these components would require
an equivalent increase in the Spar dimensions.

The pre-shaped segments in the hull of the Spar are not very efficient for arrangement
of large pieces of equipment. Smaller modules might allow for a more efficient use of
the space similar to the arrangement shown for the 500-MW(e) Spar. Vertical heat
exchangers could not be accommodated without major redesign of the Spar concept.

The 200-MW(e) is an enlarged version of the 100-MW(e) Spar. The arrangement and
operations are the same as those described for that platform.

The 500-MW(e) Spar is similar to the 100-MW(e) Spar in operation; however, there
are some differences in the arrangement. The heat exchangers are stacked and stag-
gered to provide a more efficient use of the hull volume. The demisters are mounted
directly over the evaporators and are enclosed by the hull, and there is no annular
section around the column. The ammonia storage tanks are stored adjacent to the
demisters. The space for support systems is provided at the same level as the
demister, above the heat exchangers.

The hydrostatic properties were computed for the vessel with and the cold water pipe
(CWP) attached. The curves of form are presented on Fig. 2-49. All values plotted
reflect the molded volume of the vessel.

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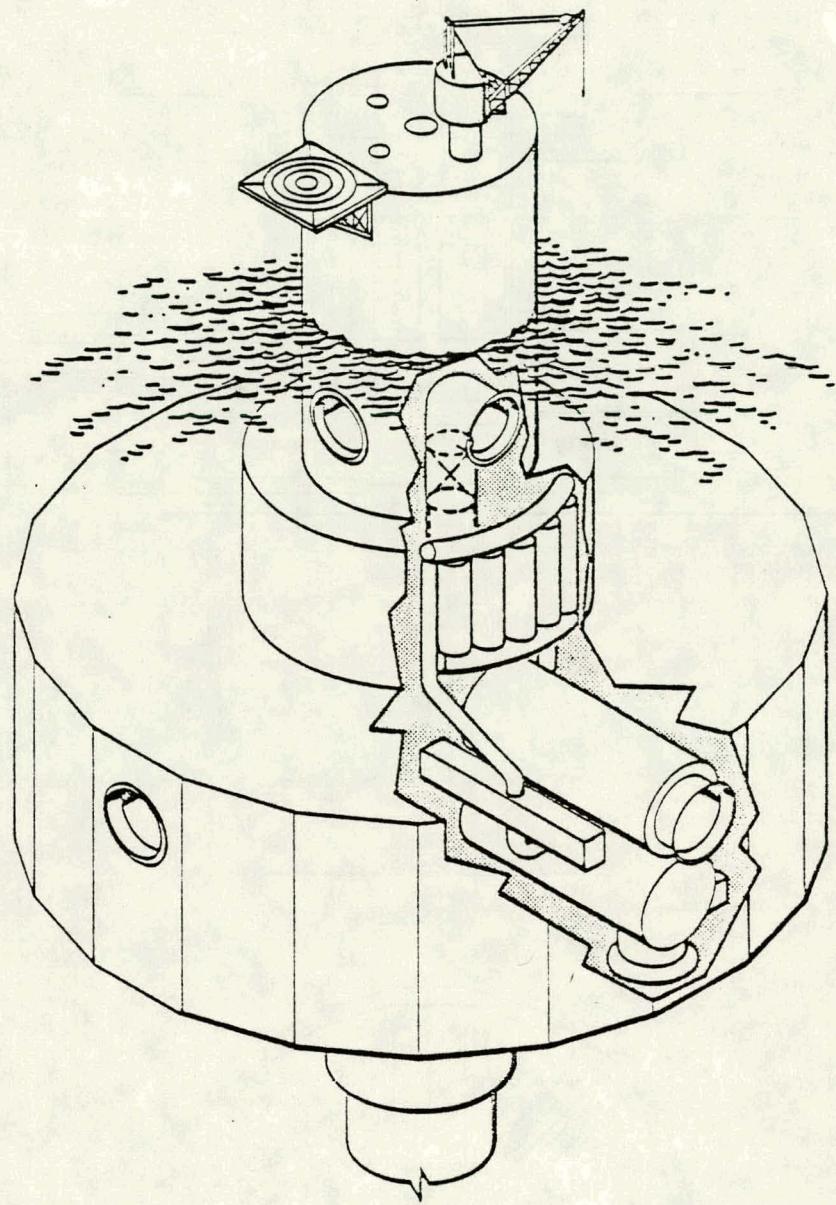
Fig. 2-47 OTEC Internal Spar for 100-MW(e) (Net) Commercial Plant
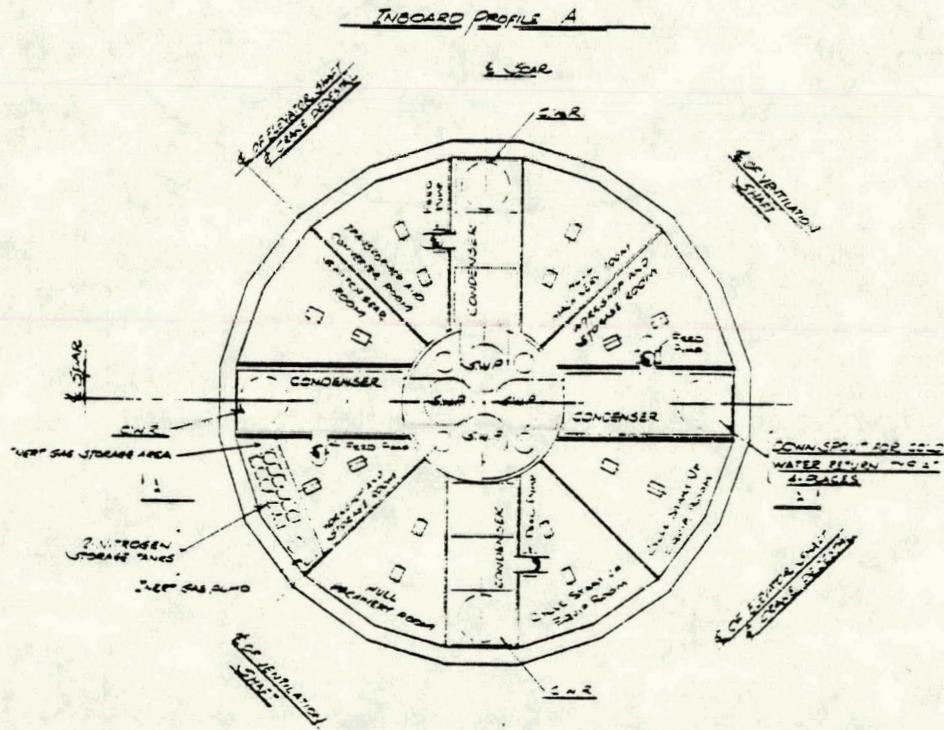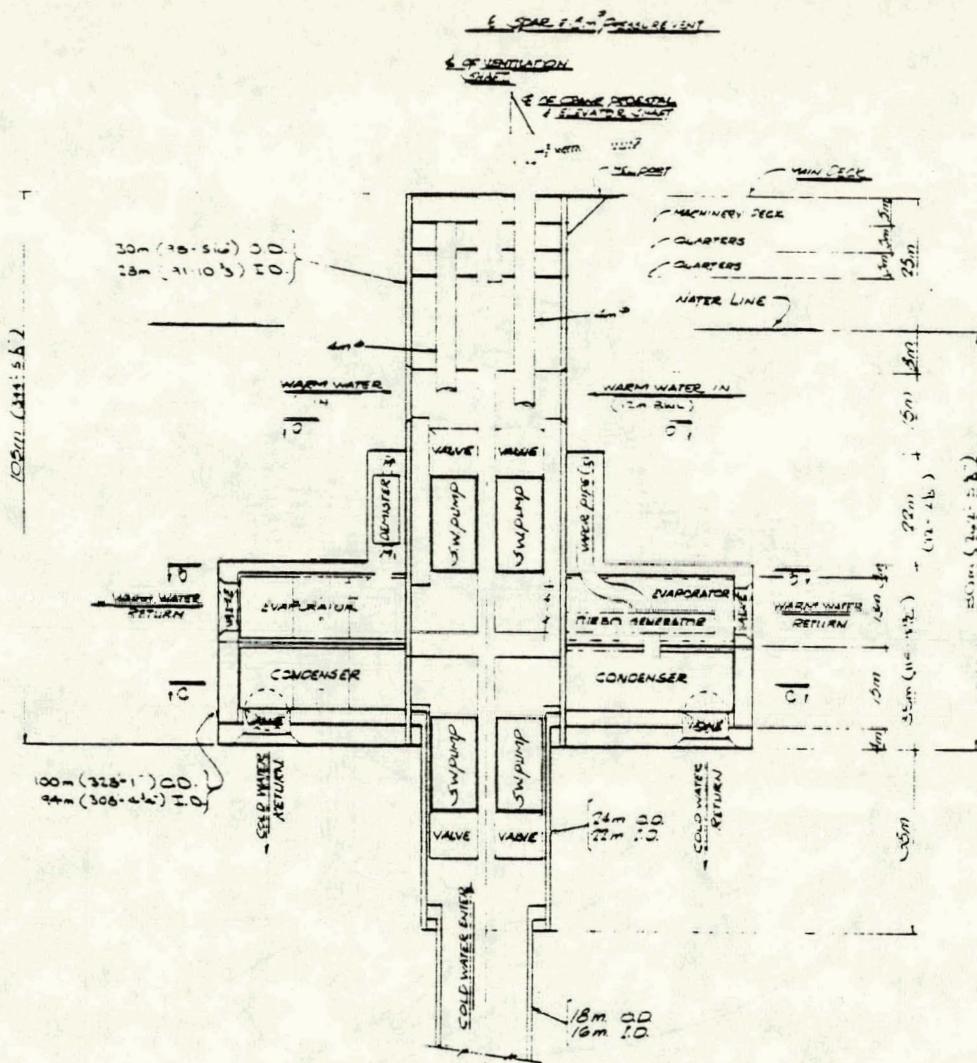
Fig. 2-48 Spar 100-MW(e) (Net) Steel

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Table 2-72

PRINCIPAL CHARACTERISTICS OF 100, 200 AND 500 MW(e) (NET) SPARS

Item	SPAR		
	100 MWe	200 MWe	500 MWe
Length (Width) (m)	100	118	156
Breadth (m)	100	118	156
Height (m)	105	100	120
Draft (m)	80	80	100
Displacement (MT)	234,000	520,000	1,440,000
Cost (x 10^{-6})	$ 442	$ 735	$ 2,323
Cost/KWe (Net)	$ 4,320	$ 3,600	$ 4,650
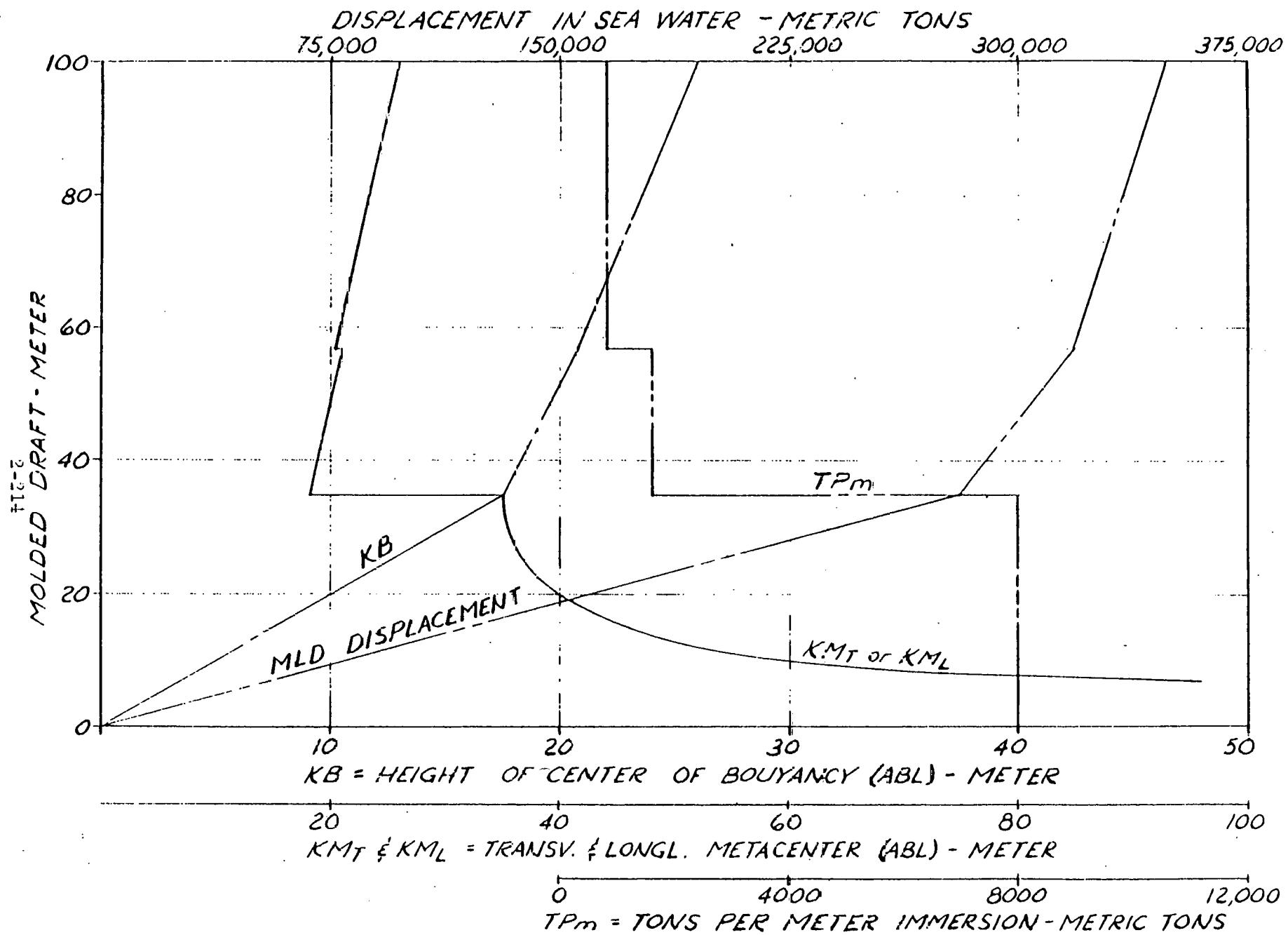
Fig. 2-49 OTEC Spar 100 MW(e) (Net) Curves of Form

The 100-MW(e) Spar weight summary is presented in Table 2-73.

2.4.6.2 Design Features. The Spar platform measures 105 m from the base of the hull to the top of the column, and normally operates at an 80 m draft. The platform consists of a 100-m-diam by 35-m-deep hull, which supports a 30-m-diam by 70-m-high column. The bottom 22 m of the column is surrounded by a 45-m-diam annular section. A freeflooding central core 28 m in diameter passes through the hull and column.

The scantlings have been sized for mild steel throughout. With an adequate cathodic protection system, and proper design and detailing, the Spar can be designed and constructed of steel to meet a 40-yr operating life.

The structure is enclosed by cofferdams of 3 m on the top and sides, and 4 m on the bottom. All three decks, the top hull, mid deck, and bottom hull, are framed similarly. The condenser/evaporator spaces, enclosed by parallel watertight walls, separate each level into four quadrants. Each quadrant is bisected by a radial wall into two segments. These segments are further divided by radial girder/column systems at the upper level and truss systems at the lower level. Each of the 20 segments is framed by a rectangular grid of beams the full depth of the cofferdams at the top and bottom, and 2 m deep at the mid-deck. Each rectangular space is further divided by deck plating supports.

The primary framing of the circumferential cofferdam spans vertically from top hull to bottom hull, the full width of the cofferdam, and is aligned with the rectangular grid beams of the decks. These vertical beams support horizontal stiffeners located on each face of the cofferdam. The section of the stiffeners and the thickness of the wall plating increases with depth.

The CWP is supported at the base of the hull and extends 920 m below the hull to reach the cold water intake depth of 1000 m. The top 30 m of the CWP is enlarged to a 24 m diam to provide sufficient area for installing the cold water systems four seawater

Table 2-73

100-MW(e) SPAR WEIGHT SUMMARY

LMSC WBS		Lightship Weight	Operating Weight
0.1	OTEC PLATFORM		
	1.0 Shell		
	1.1.1 Hull	49,000	49,000
	1.1.2 Column	6,600	6,600
	1.2 Bulkheads	8,000	8,000
	1.3 Decks	10,400	10,400
	1.4 Not Used		
	1.5 Deck Houses	500	500
	1.6 Special Structures		
	1.6.1 Demister Column	1,800	1,800
	1.6.2 Access/Vent Shafts	1,000	1,000
	1.7 Not Used		
	1.8 Foundations		
	1.8.1 Cold Water Pipe	2,500	2,500
	1.8.2 Equipment	4,700	4,700
	1.9 Ballast		
	1.9.1 Fixed Ballast	92,000	92,000
	1.9.2 Freeflooding Seawater	--	46,000
		176,500	222,500
	2.0 Seawater System		
	2.1 Cold Water Pipe		
	2.1.1 24m O.D.	2,200	1,000
	2.1.2 18m OD	51,600	22,300
	2.2 Cold Water Pumps	700	700
	2.3 Not Used		
	2.4 Warm Water Pumps	700	700

Table 2-73 (Cont.)

2.5	Water Ducts		
2.5.1	Cold Water	1,000	700
2.5.2	Warm Water	3,000	2,100
		59,200	27,500
3.0	Position Control System		
3.1	Mooring		0
3.2	Thrusters		0
4.0	Support Subsystems	3,500	3,500
5.0	Outfit and Furnishings	1,000	1,000
	PLATFORM TOTAL	240,200	254,500
0.2	ELECTRICAL TRANSFER SYSTEM	200	200
0.3	POWER SYSTEM (See Table 3-1 for Details)	19,600	32,300
0.4	MISCELLANEOUS		
1.0	Seawater Ballast		39,000
2.0	Consumables		5,000
3.0	CWP Install. Equip.	3,000	3,000
		3,000	47,000
	TOTAL WEIGHT WITH CWP	213,000MT	334,000MT
	TOTAL WEIGHT WITHOUT CWP	161,400MT	310,700MT

pump modules. Each SW pump drives the cold water through a 90-deg elbow into the condenser, and out the seawater discharge, which is at right angles to the condenser. The cold seawater discharges at a depth of 80 m and is directed downward which should satisfy the requirement of cold water discharge at 100-m depth.

The centerline of the warm water intakes is 12 m below the operating water line. This depth can easily be varied by ballasting or deballasting to reach the optimum intake elevation as dictated by the environments or site location. The warm water system SW pumps are installed in the critical core of the column at right angles to the warm water intake. The SW pump drives the warm water through a 90-deg elbow into the evaporator, and out the seawater discharges. The warm seawater discharges horizontally at a 55-m depth, and is parallel to and 43 m from the warm water intake, which exceeds the limits set up to prevent mixing and recirculation of the warm water intake and discharges.

The Spar is a symmetrical platform; and therefore, there is no need to orient the platform to minimize aero and hydrodynamic drag. It is also doubtful whether recirculation of the warm water intake and discharge would be affected by platform orientation, so there is no provision for azimuthing thrusters on the Spar.

The Spar will be held on location by a multipoint fixed mooring system.

The electrical power generated by the OTEC system is conditioned before it is transmitted from the platform. The switchgear, transformers, and conversion equipment for the entire 100-MW(e) system is located in the lower level of the hull in two adjacent segments. The power cables are routed to a common cable junction box which penetrates the hull for transmission from the platform.

The OTEC utilizes a closed-loop ammonia system for its power generation. The ammonia is vaporized in the evaporators, which are located on the upper level in the hull. The vapor leaves the evaporator and passes through the demisters which are located in the annular section above the hull. After the vapor is condensed, it is pumped back into the evaporator to complete the cycle. The total length of the ammonia vapor piping for a 100-MW(e) Spar is 475 m; the total length of ammonia liquid piping is 130 m.

The main power system auxiliaries are all located in the hull. The ammonia storage tanks are segregated in two segments of the upper level of the hull. The inert gas purge system is located on the lower level of the hull, along with the system startup power supply.

2.4.6.3 Constructability.

(a) Facility Requirements

Due to the large diameter of the Spar hull, 100 m (328 ft), few of the facilities surveyed are of sufficient size in which to build the spar hull as a single unit. Drydocks of sufficient size do exist, such as the Blount Island, Jacksonville, Florida, Offshore Power Systems facility. Facilities of this size are few and possibly not available when needed. By dividing the hull into modules, each 71 × 40 m (233 × 132 ft) module will fit within existing drydocks.

The draft of a module including machinery and with eight 10-m-diam spheres attached for added flotation is 12.2 m (40 ft). The following docks, from an LMSC list, meet this requirement: Newport News Shipbuilding and Drydock Co., 1100 × 135 × 40 ft; Triple A Shipyard, Hunters Point, 1092 × 143.2 × 43 ft. After launch, a shallow water shoreside depth of 14.3 m (47 ft) is required before towing out to sea.

A new drydock capable of containing the 100-m-diam spar hull would require a draft selected from the following requirements. Hull machinery at launch – draft 14.3 m (47 ft). Hull and machinery with flotational assistance of 15,803 MT displacement at launch – draft 12.2 m (40 ft).

(b) Construction Methods

Three construction options are described. A summary of these optional methods is shown in Table 2-74.

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Table 2-74

SUMMARY OF CONSTRUCTION METHODS – SPAR

		Modular Construction		Single Unit Construction
		Option I	Option II	Option I-A
DRY DOCK	Draft Required Facility Required Flotation Work Portion Work Completed	12.2m (40') 71x40m (233x132') Existing 8 Spheres 10m dia. 78.6% 78.6%	12.2m (40') 71x40m (233x132') Existing 8 Spheres 10m dia. 78.6% 78.6%	12.2m (40') 100x100m (328x328') New 32 Spheres 10m dia. 82.3% 82.3%
SHELTERED WATER	Draft Required Flotation Work Portion Work Completed	12.2m (40') 8 Spheres 10m dia. (x4) 3.7% 82.3%	13.4m (44') 8 Spheres 10m dia. (x4) 3.7% 82.3%	12.2m (40') 32 Spheres 10m dia. 0% 82.3%
DEEP WATER	Work Portion Work Completed	17.7% 100%*	17.7% 100%*	17.7% 100%*

* Excluding mobilization – CWP installation, crane installation and removal, towing.

(1) Option I – Modular Construction Using Existing Facilities

The cylindrical 100-m-diam hull is built as four separate, structurally
identical modules, each containing a condenser, evaporator, and assoc-
iated equipment. A module measuring 71 × 40 m (233 × 132 ft) fits within
existing dock facilities having 40-ft draft capability. Assuming an average
density of each module equal to that of the hull as a whole, additional
flotation is needed to achieve a maximum 40-ft draft. Spheres, 10 m
in diam, or bags or vessels of equal volume, are required. They are
placed alongside the module and are completely submerged at 40-ft
draft. The symmetry and duplication of the hull segments lend them-
selves to modular construction with reuse of tools and jigs and berthing
supports.

Each module consists of a quarter-hull pie-shaped segment containing
all equipment and machinery including de-misters. Without the additional
flotation a 47-ft-deep dock is required.

After floating out, the modules are connected together in protected
shallow water. The draft is 12.2 m (40 ft) leaving 22.8 m of structure
above water for connections. Since each module needs its own walls
to at least water level the assembled modules are separated by double
walls to that level, the space between the walls being flooded below 12.2 m,
requiring cofferdams in these areas for damage protection. The hull
central well wall at this stage is up to the level of the demister compart-
ment top. A crane or derrick is assembled over the well. This arrange-
ment is advantageous in that the crane or derrick, being tied to the hull,
does not experience motions relative to the hull, unlike a separate barge
crane alongside the hull. This is of great importance at the deep water
site when relative motion between the hull and sections being installed,
such as the CWP and saltwater pumps, would make construction difficult.
Sections being installed are placed aboard the hull top deck by barge

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crane and from there lifted and lowered down the well by the onboard crane. The upper CWP section is loaded and suspended in the hull column, while the hull is still in shallow water.

The saltwater pumps located in the upper CWP are installed and the section is lowered to the well base, where the connection is made underwater. Saltwater pumps are installed in the hull well and the crane is disassembled and removed. The flotation bags or collars are removed and concrete and water ballast added until the water level is just below the top of the well. Using a barge crane, the upper column above the hull well is installed. The hull is further ballasted and the quarters and heliport are installed on the column top.

(2) Option I-A — Unit Hull Construction Using New Facilities

The hull is fabricated as one unit in a 350 ft × 350 ft × 40 ft dock, which would have to be constructed. The upper CWP section is suspended within the hull well. All power plant and auxiliary machinery is installed. This results in a vessel draft of 47 ft. To reduce the draft to 40 ft for float-out, 32 spheres, 10 m in diam, or a peripheral collar, 10 × 5 m, are attached to the vessel sides. After float-out, the construction sequence follows that of Option I.

(3) Option II — Construction at Sea Without Integrated Crane

This option differs from I and II in that no crane or derrick is assembled on board. All lifts are accomplished from shore or barge cranes. Since the large diameter of the hull makes it difficult for a crane at sea to reach the center well, the hull would be ballasted to below the waterline to allow a barge crane to approach the top of the well. Deballasting would occur after certain lifts to allow connections to be made between components in the well and the hull, above water level.

2.4.6.4 Operability.

(a) Maintenance

All power system, electrical transmission system, and vessel service systems are accessible from within the hull of the vessel. Access to the sea water pumps is not convenient on the Spar. The pump must be isolated from the sea by closing the valves above and below the pump, the seawater must removed, and then the pump be accessed through the seawater piping. As described previously for the Ship, the Spar will have sufficient on board facilities to handle all minor repairs and complete equipment overhauls. The Spar can also be serviced by a mobile support vessel for major repairs.

The size of a removable component is limited by the 4 m diam access shafts, while the Spar is operating. If the Heat Exchangers have to be removed, the Spar will deballast to expose the hull; and predetermined access hatches will be opened in the hull, and the heat exchangers will be removed by a floating crane barge. The existing arrangement on the Spar will allow the heat exchangers to be retubed in place, so removal should be a very rare occurrence.

(b) Operation

The only significant difference between the operation of the Spar and the Ship is in the location of the work spaces. The extreme depth of the lower hull of the Spar at operating draft, and the limited access to and from the hull present problems which will affect the operation of the Spar.

Emergency escape procedures will have to be developed for hull, as well as the overall vessel. Ventilation contingencies for continued air supply, as well as isolation of gas leaks will also be extremely critical for the Spar. The great distance between the work spaces and the Quarters should be provide a buffer from noise and vibration, which would be a benefit not realized on the Ship; however, in general the Spar will have more potential operation problems than the Ship.

(c) Performance

(1) Intact Stability

This vessel is designed to satisfy the requirements of the American Bureau of Shipping. ABS measures intact stability by the ability of the vessel to withstand the overturning forces of a severe wind and accompanying waves.

A measure of the stability of the intact vessel is a comparison between the overturning energy created by wind and waves and the righting energy created by the heeled vessel. The amount by which the righting energy exceeds the overturning energy upto the limiting angle is a measure of the vessel's ability to resist capsizing or downflooding. The ABS rules require that the area under the righting moment curve at be least 30 percent greater than the area under the heeling moment curve upto some limiting angle. The heeling moment curve used is that of a 51.5 m/sec (100 knots) wind. The limiting angle is that corresponding to either the second intersection of the two curves, beyond which the overturning moment exceeds the righting moment, or the occurence of downflooding, whichever is less.

The intact stability of the vessel has been evaluated for three conditions:

- Light draft (in transit)
- Operating draft (80 m) with CWP
- Operating mode without CWP (breaks off)

For each case, the KG value was calculated. In each case, the area ratio between the righting moment and the heeling moment curves was greater than 1.3. The vessel has sufficient stability in the intact condition to withstand anticipated environmental loads to a degree established as acceptable by ABS.

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(2) Damaged Stability

Damaged stability calculations are performed to assure that the vessel
will survive flooding of certain spaces due to damage without capsizing
or sinking or flooding into additional spaces. The extent of damage
which a vessel should be able to tolerate and the environment loads
which it should be able to resist are established in the ABS Rules.

This assumes that damage can occur at exposed portions of column
located on the periphery of the vessel. The vertical range in which
damage may occur extends from 1.5 m above the waterline to 1.5 m
below. The vertical extent of damage is assumed to be 3.0 m occuring
anywhere within the assumed vertical range. The horizontal extent is
assumed to be 45 deg and the assumed depth of penetration if 1.5 m.

Therefore, if a horizontal flat is within the vertical range of damage, it
must be assumed damaged. Also, interior bulkheads must be located
inboard of the assumed depth of damage if they are to be assumed intact.

The overturning energy of wind and wave is assumed to act upon the
damaged vessel, adding a heeling moment to that caused by the flooding
water. The wind heeling moment computed in the same manner as for
the intact stability, is that created by a 25.8 m/sec (50 knots) wind.
The ABS Rules require that the flooded vessel have sufficient stability
to sustain the heeling energy of the wind without capsizing or heeling
over to an angle at which down flooding can occur.

At operating draft, annular sections of the column is partitioned by
horizontal and vertical watertight flats, so flooding is limited to less
than 300 MT.

At transit draft the hull cofferdam protects the interior spaces from flooding. Flooding is limited to less than 1000 MT if the hull is damaged. The study shows that the vessel has sufficient stability in the damaged condition to withstand anticipated environmental loads to a degree established as acceptable by ABS.

(3) Spar Motions and Cold Water Pipe Loads

The motions of the 100 MWe Net spar platforms are summarized in Table 2-75. The pitch and roll motions are the smallest of the platforms when compared with the deep attachment of the CWP. The loads in the CWP are moderate for the deep attachment point. The pipe dynamic loads are greatly reduced (1/2) by location of the attachment of the CWP near the center of the hull.

2.4.6.5 Risks. A power availability risk, as for the submersible is related to the necessity for surfacing by blowing ballast for removal of major power system components or other maintenance activities involving surface support facilities.

Table 2-75

CALCULATED SEAWAY RESPONSE FOR SPAR PLATFORM
IN HEAD AND BEAM SEAS, CONCRETE CWP,
$E = 0.3 \times 10^6$ PSI, 10^9 LB-FT/RADIAN
CWP ATTACHMENT STIFFNESS

Response	Units	Significant Amplitude for Significant Wave Height			
		20 ft	35.9 ft	45.8 ft	58.1 ft
HEAD SEAS					
Surge	ft	0.8	3.0	4.7	8.7
Heave	ft	0.7	2.8	4.4	8.2
Pitch	deg	0.3	0.9	1.4	2.5
Max. Acceleration	ft/sec^2	0.3	0.8	1.2	1.8
CWP Rotation	deg	1.0	2.7	4.1	7.2
Max. Bending Moment	lb-ft	2.09×10^8	5.82×10^8	7.94×10^8	1.16×10^9
Max. Bending Stress	psi	3.05×10^2	8.48×10^2	1.16×10^3	1.69×10^3
Max. Shear Force	lb	9.93×10^5	2.85×10^6	3.84×10^6	5.12×10^6
BEAM SEAS					
Sway	ft				
Heave	ft				
Roll	deg				
Max. Acceleration	ft/sec^2		Same as Head Seas		
CWP Rotation	deg				
Max. Bending Moment	lb-ft				
Max. Bending Stress	psi				
Max. Shear Force	lb				

2.4.6.6 Costs.

(a) Construction Cost – SPAR

The estimated costs to construct the OTEC spar in an existing facility, assuming no draft, width or length limitations are shown in Table 2-76 This is the base used in estimating the cost to build the Spar when considering construction facility capabilities.

Using the cost factors discussed in Section 2.4.1.7 and the percent construction completed in each phase as shown in Table 2-74, a cost of each construction option was developed. A summary of these costs is shown in Table 2-77.

(b) Mobilization Costs – Spar

In addition to the costs mentioned in Section 3.6.2, there are additional costs in the case of the Spar due to construction that must be delayed until after CWP installation, namely, sea-water pumps and quarters installation. Employing the mobilization times presented in Section 2.4.6.7 the following costs are determined:

Cost, min. = 300,000 × 26.25 = $ 7,875,000
Cost, max. = 300,000 × 70   = $21,000,000

Total mobilization costs – Spar:

39,750,000 + 7,875,000 = 47,625,000
96,000,000 + 21,000,000 = 117,000,000

$48 – 117 million

Table 2-76

PLATFORM CONSTRUCTION COSTS – SPAR – STEEL
(UNCORRECTED FOR ERECTION COMPLEXITY)

		$/MT	MT	COST x105
1.0	Hull and Structure			
1.1	Shell			
1.1.1	Hull	3,100	49,000	151.9
1.1.2	Column	4,300	6,600	28.4
1.2	Bulkheads	3,100	8,000	24.8
1.3	Decks	3,100	10,400	32.2
1.4	Not Used			
1.5	Deck Houses	2,600	500	1.3
1.6	Special Structures			
1.6.1	Demister Column	4,300	1,800	7.8
1.6.2	Access/Vent Shafts	2,600	1,000	2.6
1.7	Not Used			
1.8	Foundations			
1.8.1	CWP	3,100	2,500	7.8
1.8.2	Equipment	3,100	4,700	14.6
1.9	Permanent Ballast	115	92,000	10.6
			176,500	282.0
2.0	Not Used			
3.0	Position Control System			0.0
4.0	Support Subsystem			
4.1	Cathodic Protectors/Coating			10.5

Table 2-76 (Cont.)

4.2	Machinery and related piping			3.0
	& Elevators			
	& Deck Cranes			
	& Diesel Generators (Quarters)			
	& Emergency Generators (Quarters)			
	& Hoists, Tuggers, Forklifts			
	& Compressed air system			
4.3	Hull Piping Systems/w Machinery			13.0
	• Ballast			
	• Bilge			
	• De-Ballast Vent			
	• Sonndry			
	• Engine Cooling			
	• Compressed Air			
	• Lube Oil			
	• Fuel Oil			
	• Fresh Water			
4.4	HVAC			13.4
4.5	Safety Equipment			1.0
	• Fire Protection			
	• Life Boats			
	• Life Rafts			
4.6	Electrical Work (Misc.)			1.3
4.7	Vessel Management			3.6
4.8	Accomodation			2.5
4.9	Workshops (Misc.)			1.0
4.10	Radio and Communications			0.2
				49.5
5.0	Installation of OFE			
	• DACS	500	26,000	13.0
	• Sea Water System			
	• CWP Handling Equipment			
	• Energy Transfer System			
	• Power System			
	TOTAL		$344,500,000	

Table 2-77

SUMMARY OF COSTS OF CONSTRUCTION OPTIONS — SPAR — STEEL

Construction Location	Work Description	Option I			Option I-A			Option II		
		Weight	Unit Cost	Cost	Weight	Unit Cost	Cost	Weight	Unit Cost	Cost
DRY DOCK (Cost Factor) = 1	Structure Equip. Instl.	Modular			80,215 24,500	3,200 500	256.7 12.3	Modular		
SHORE SITE (Cost Factor) = 1.25	Structure Equip. Instl.	80,215 24,500	3,200 500	320.9 15.3				80,215 24,500	3,200 500	320.9 15.3
SHALLOW WATER (Cost Factor) = 2	Structure Equip. Instl. Concrete Ballast									
ON-SITE (Cost Factor) = 3	Structure Equip. Instl. Concrete	4,285 1,500* 92,000	3,200 500 115	41.1 2.3 31.7	4,285 1,500* 92,000	3,200 500 115	41.1 2.3 31.7	4,285 1,500* 92,000	3,200 500 115	41.1 2.3 31.7
Subtotal				411.3			344.1			411.3
Support Subsystems				49.5			49.5			49.5
Total				460.8			393.6			460.8
	Units	mt	$/mt	$ million	mt	$/mt	$ million	mt	$/mt	$ million

* Sea-Water Pumps

2.4.6.7 Schedule. Schedules for mobilization are based on the following breakdown of construction sequence times:

Lift CW sea-water pumps on-board:	1 day
Lower CW sea-water pumps down column:	1 day
Make Connections between pumps and hull:	3 days
Lift WW sea-water pumps on-board:	1 day
Lower WW sea-water pumps down column:	1 day
Make connections between pumps and hull:	5 days
Remove on-board gantry crane:	5 days
Lift and place quarters onboard:	1 day
Make connections between quarters and Spar:	<u>5 days</u>
	21 days

Min. worktime = 21/80 percent = 26.25 days

Max. worktime = 21/30 percent = 70 days

2.4.6.8 Summary. The Spar configuration provides an adequate platform for the specified internal power system. The accomodation of the height of the demisters and the length of the heat exchangers has driven the size of the equipment area. The large displacement of this Spar is a result of the sizes and proportions of the power system components. Integration of an internal power system with the Spar concept should reduce the comparatively high cost for the Spar. Construction methods which avoid the high complexity factor (3x) could provide further reduction in platform costs.

2.4.7 Spar — Detachable Power Module

2.4.7.1 General Description. The general arrangement of the 100-MW(e) OTEC Spar with detachable power modules is shown on Fig. 2-50. There are four detachable modules for the 100 MW(e) (net) configuration. The heat exchangers, seawater pumps, demisters, and turbine-generators are housed within the detachable modules. The modules are attached to a central Spar which contains the ammonia storage tanks, inert gas purge system, data acquisition and control system, electrical conversion and transmission equipment, cycle startup power plant, and miscellaneous vessel support systems. The accommodation spaces, and material handling system are also on the Spar.

2.4.7.2 Design Features. The Spar and power modules are made up of cylindrical shapes. The 40-m and 22-m-diam columns are double-skin watertight construction throughout their entire height. The detachable modules are single-skin watertight construction.

The principal characteristics of the Spar and detachable modules are:

Spar

Lower column diameter:	
Upper column diameter:	40 m (131 ft)
Overall height:	140 m (459 ft)
Operating Displacement:	105,900 MT
Lightship weight:	80,300 MT

Power Module

Column Diameter:	13 m (43 ft)
Overall height:	95 m (312 ft)
Displacement (Submerged):	18,000 MT
Lightship weight:	11,000 MT

Spar With Power Modules (4)

Operating Draft:	115 m (459 ft)
Operating Displacement:	117,900 MT
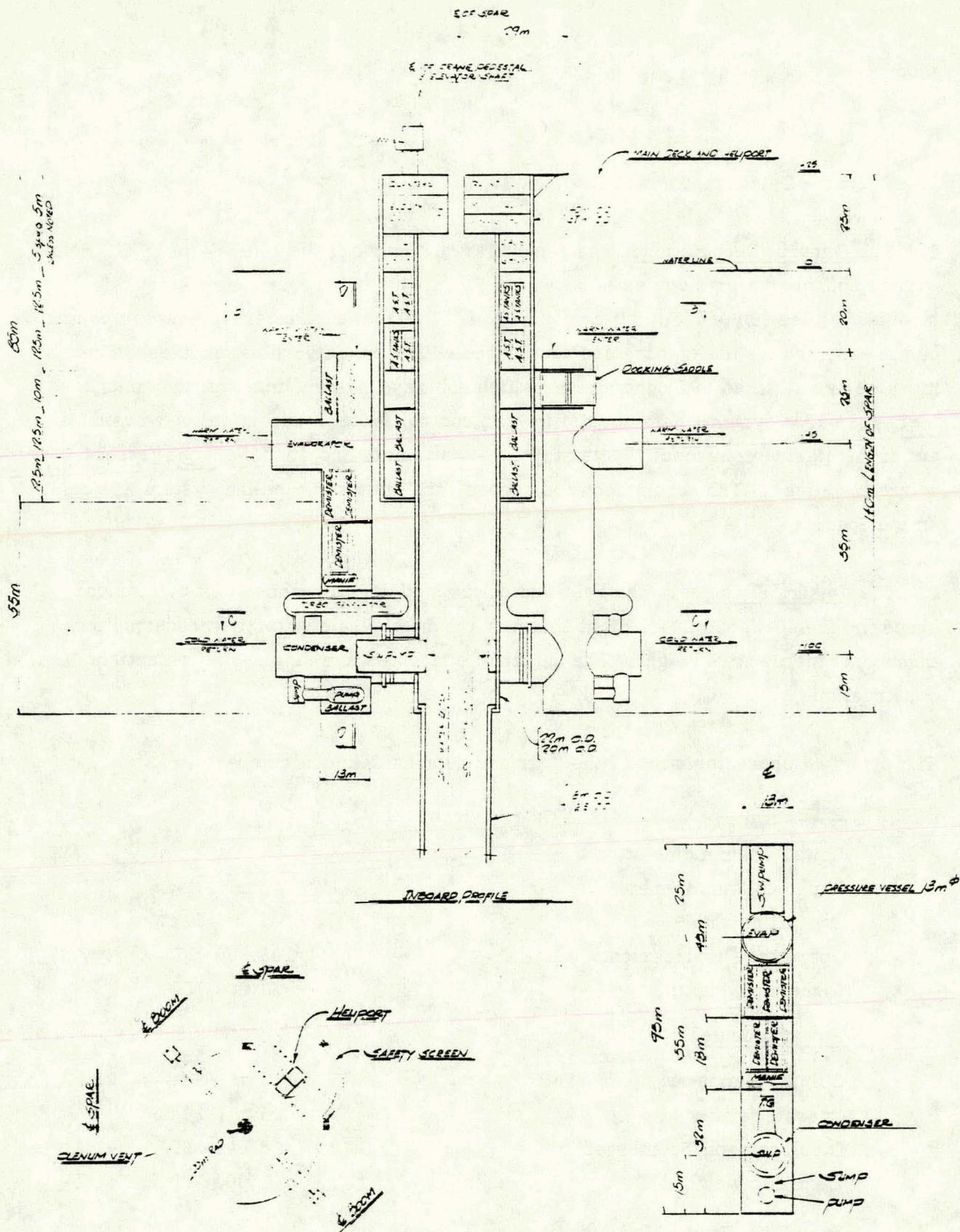
Fig. 2-50 General Arrangement of 100-MW(e) Spar Power Modules

2-234
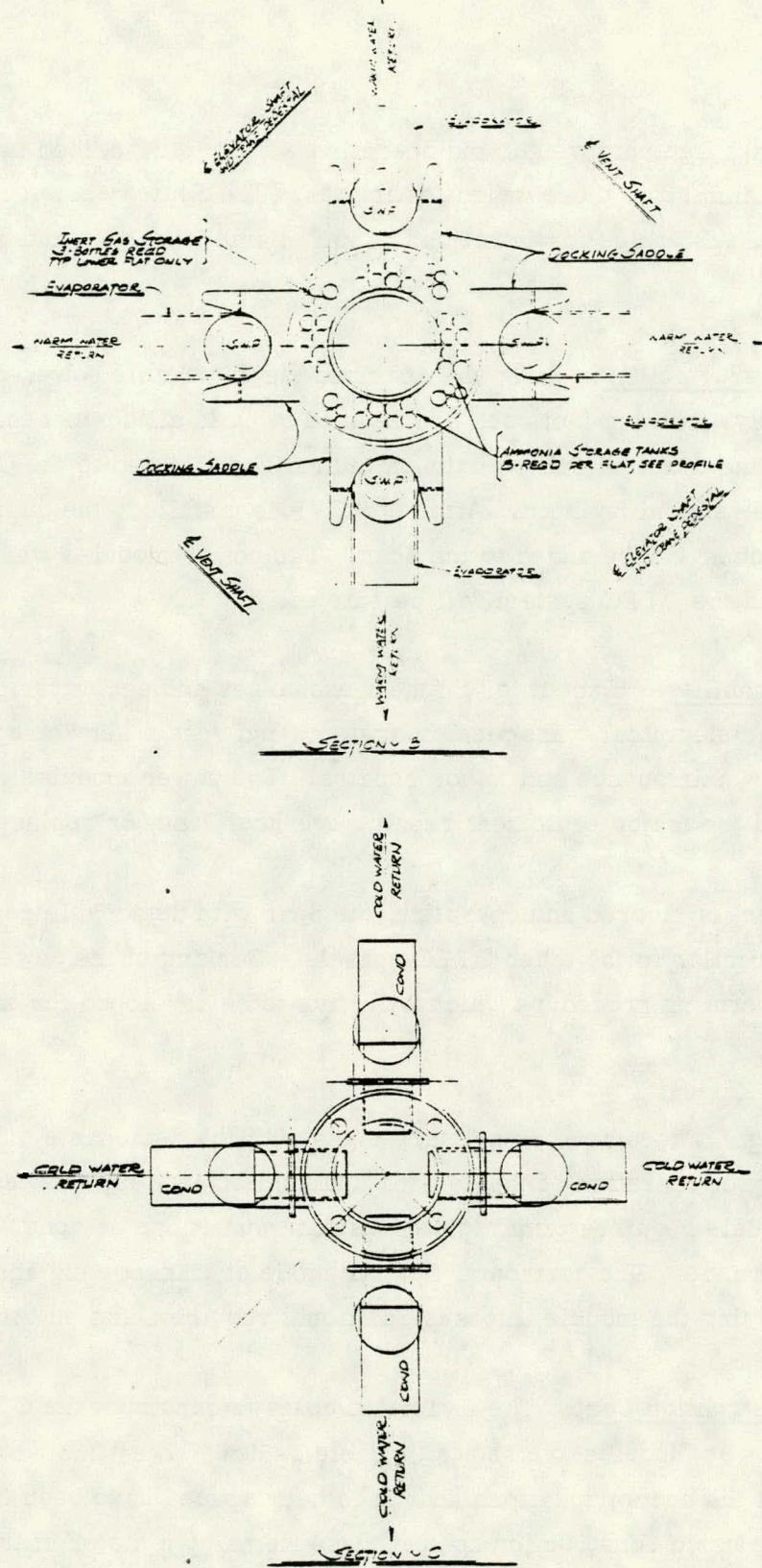
Section B

Section C

Fig. 2-50 (Cont.)

The definition of lightship weight and operating weight is described in Section 2.4.6. Table 2-78 summarizes these weight estimates. The Spar with detachable power modules meets ABS rules for intact and damaged stability, with and without the CWP attached.

2.4.7.3 Constructability. Since the Spar and the detachable power modules will be built separately, existing facilities can be used to build all components of the system. The Spar and the modules will be built on their sides, floated to the OTEC site, and upended to the vertical position. After the CWP is installed, the quarters and machinery spaces will be added to the Spar. The power modules will then be attached to the Spar and the OTEC system will be started.

2.4.7.4 Operability. Except for the heat exchanges and sea water pumps, all power system, electrical transmission system, and vessel service systems are accessible for maintenance and minor repairs. The power modules can be detached and drydocked for major equipment repair, overhaul, and/or replacement.

Once the vessel is moored and operating, the Spar with detachable power modules will operate similar to the other OTEC vessels. Docking of the power modules will be a major operating procedure which will have to be developed for this OTEC configuration.

2.4.7.5 Risks. There are two primary risks with the detachable module Spar. The reliability of operation of the docking and seal off system between the Spar and the power module requires effort to demonstrate that it can be done with high or fail safe assurance. The horizontal floating mode of transporting and the horizontal mode of servicing the module imposes additional requirements on the power system.

2.4.7.6 Construction Cost. The estimated costs to construct the OTEC Spar with detachable Power Modules are shown in Table 2-79. The estimated cost for installation of the accommodations and machinery spaces have been included by increasing the basic construction cost of these items by a factor of three. Mobilization costs developed for the other OTEC configurations can be used for the Spar.

2.4.7.7 <u>Schedule.</u> It is estimated to require 43 months to construct the spar hull.

2.4.7.3 <u>Summary.</u> The detachable power modules on the spar present a way of optimizing the use of the volume inside the basic spar. Some additional structure must then be provided for the detachable module. The design approach presented here has satisfactorily accommodated the specified baseline power system. Further reductions in platform (core + module) costs should be attainable with power system components which are fully integrated into the platform.

Table 2-78
SPAR WITH DETACHABLE POWER MODULES WEIGHT ESTIMATE

0.1A OTEC PLATFORM SPAR		Lightship Weight Metric Tons	Operating Weight Metric Tons
1.0	SHELL		
1.1	22mø Column	2060	2060
1.2	40mø Spar	11040	11040
1.3 - 1.4	Not Used		
1.5	Deck Houses	2500	2500
1.6	Special Structures		
1.6.1	Docking Saddle (Upper)	400	400
1.6.2	Docking Disc (Lower)	1930	1930
1.6.3	Access/Vent Shafts	260	260
1.7	Not Used		
1.8	Foundations		
1.8.1	Cold Water Pipe	2500	2500
1.8.2	Equipment	1500	1500
1.9	Ballast		
1.9.1	Fixed Ballast		
1.9.2	Freeflooding Ballast	---	41200
	TOTAL	22,190	63,390
2.0	SEAWATER SYSTEM		
2.1	Cold Water Pipe	51,300	22,200
3.0	POSITION CONTROL SYS	---	---
4.0	SUPPORT SUBSYSTEMS	2000	2000
5.0	OUTFIT AND FURNISHINGS	500	500
	PLATFORM(SPAR)TOTAL	75,990	98,090
0.2	ELECTRICAL TRANSFER SYSTEM	200	200
0.3	POWER SYSTEM		
1.0 - 3.0	Not Used		
4.0	AMMONIA SYSTEM		
4.1	Not Used		
4.2	Not Used		

Table 2-78 (Cont.)

4.3	Misc. Piping	20	20
4.4	Ammonia Compressor	40	40
4.5	Not Used		
4.6	Ammonia Vacuum Pump	10	10
4.7	Ammonia Storage Tanks	1,050	2,610
	TOTAL	1,120	2,680

0.4   MISCELLANEOUS

1.0	SEA WATER BALLAST		7,720
2.0	CONSUMABLES		4,200
3.0	CWP INSTALLATION EQUIP	3,000	3,000
	TOTAL	80,310MT	105,890MT

Table 2-78 (Cont

0.1B	OTEC PLATFORM DETACHABLE POWER MODULE	Lightship Weight Metric Tons	Operating Weight Metric Tons
1.0			
1.1.1	Vertical Cylinder	3,660	3,660
1.1.2	Horiz. Cylinder	760	760
1.1.3	Turbo-Genr. Enclosure	250	250
1.2 - 1.7	Not Used		
1.8	Foundations		
1.8.1	Not Used		
1.8.2	Equipment	300	300
1.9	Ballast		
1.9.1	Fixed Ballast		
1.9.2	Freeflooding Ballast		4,360
2.0	SEAWATER SYSTEM	4,970	9,330
2.1	Not Used		
2.2	Cold Water Pumps	175	175
2.3	Not Used		
2.4	Warm Water Pumps	175	175
2.5.1	Not Used		
2.5.2	Warm Water	300	300
		650	650
3.0	POSITION CONTROL SYSTEM		
3.1 - 3.2	Not Used		
3.3	Docking Equip.	200	200
		200	200
4.0	SUPPORT SUBSYSTEMS	400	400
5.0	OUTFIT AND FURNISHING	100	100
	PLATFORM TOTALS	6,320	10,680
0.2	NOT USED		
0.3	POWER SYSTEM		
1.0	Heat Exchangers (2) *Freeflooding	4,125	4,125*
2.0	TURBO-GENERATORS (1)	205	205

Table 2-78 (Cont.)

3.0	DEMISTERS (5)	210	215	
4.0	AMMONIA SYSTEM			
4.1	Vapor Piping	35	40	
4.2	Liquid Piping	25	75	
4.3	Not Used			
4.4	Ammonia Compressor (1)	10	10	
4.5	Ammonia Feed Pump	25	25	
		4,695	4,695	

0.4 <u>MISCELLANEOUS</u>

1.0	SEA WATER BALLAST		2,425
2.0	CONSUMABLES		200
3.0	NOT USED		
	TOTAL		2,625

TOTAL ONE MODULE	10,955MT	18,000MT
TOTAL FOUR MODULES	43,980MT	72,000MT
TOTAL SPAR & MODULES	124,290MT	177,000

Table 2-79

SPAR WITH DETACHABLE MODULES COST ESTIMATE

0.1A OTEC PLATFORM SPAR

		$/MT	MT	COST x10^6
1.0	SHELL			
1.1	23m⌀ Column	4300	2060	8.9
1.2	40m⌀ Spar	3100	11040	34.2
1.3 - 1.4	Not Used			
1.5	Deck Houses	7800*	2500	19.5
	*Installed on Site			
1.6	Special Structures			
1.6.1	Docking Saddle (Upper)	3100	400	1.2
1.6.2	Docking Disc (Lower)	3100	1930	6.0
1.6.3	Access/Vent Shafts	2600	260	0.7
1.7	Not Used			
1.8	Foundations			
1.8.1	Cold Water Pipe	3100	2500	7.8
1.8.2	Equipment	3100	1500	4.7
	TOTAL		22,190	83.0

2.0   NOT USED

3.0   POSITION CONTROL SYSTEM

4.0   SUPPORT SUBSYSTEM

4.1   Cathodic Protectors/Coating   3.6

4.2   Machinery and related piping   2.6
       Elevators
       Deck Cranes
       Diesel Generators (Quarters)
       Emergency Generators (Quarters)
       Hoists, Tuggers, Forklifts
       Compressed Air System

4.3   Hull Piping System/w Machinery
       Ballast   7.1
       Bilge
       De-Ballast Vent
       Sounding
       Engine Cooling
       Compressed Air
       Lube Oil
       Fuel Oil

Table 2-79 (Cont.)

Fuel Oil

4.4	HVAC	2.4
4.5	Safety Equipment	1.0
	Fire Protection	
	Life Boats	
	Life Rafts	
4.6	Electrical Work (Misc.)	1.2
4.7	Vessel Management	3.6
4.8	Accommodation	2.5
4.9	Workshops (Misc.)	1.0
4.10	Radio and Communications	0.2
5.0	INSTALLATION OF OFE	6.5
	(13,000MT @ $500/MT)	
	DACS	
	Sea Water System	
	CWP Handling Equipment	
	Energy Transfer System	
	Power System	

TOTAL 4 and 5	31.7
TOTAL SPAR	114.7

Table 2-79 (Cont.)

0.1B OTEC PLATFORM - EXTERNAL POWER MODULE

		$/MT	MT	COST x10⁶
1.0	SHELL AND STRUCTURE			
1.1.1	Vertical Cylinder	4300	3660	15.7
1.1.2	Horiz. Cylinder	4300	760	3.3
1.1.3	Turbo-Gener. Enc.	4300	250	1.1
1.2 - 1.7	Not Used			
1.8	Foundations			
1.8.1	Not Used			
1.8.2	Equipment	3100	300	0.9
			4,970	21.0

2.0   NOT USED

3.0   POSITION CONTROL SYSTEM

4.0   SUPPORT SUBSYSTEMS

4.1   Cathodic Protectors/Coating

4.2   Machinery and related piping   0.1
       Elevators
       Deck Cranes
       Diesel Generators (Quarters)
       Emergency Generators (Quarters)
       Hoists, Tuggers, Forklifts
       Compressed Air System

4.3   Hull Piping Systems/w Machinery   1.1
       Ballast
       Bilge
       De-Ballast Vent
       Sounding
       Engine Cooling
       Compressed Air
       Lube Oil
       Fuel Oil

4.4   HVAC   0.3

Table 2-79 (Cont.)

4.5	Safety Equipment Fire Protection Life Boats Life Rafts	--
4.6	Electrical Work (Misc.)	0.1
4.7	Vessel Management	--
4.8	Accommodation	--
4.9	Workshops (Misc.)	--
4.10	Radio and Communications	--
5.0	INSTALLATION OF OFE (10,000MT@$500/MT) DACS Sea Water System Energy Transfer System Power System	5.0 --

TOTAL 4 and 5	6.6
TOTAL ONE MODULE	27.6
TOTAL FOUR MODULES	110.4
TOTAL SPAR AND MODULES	$225.1

2.4.8 Prestressed Concrete Hull

T. Y. Lin International (TYLI) was given the task of studying and comparing the
hull configuration for six different OTEC platforms in prestressed concrete. Five
hulls have been designed in steel by the two naval architectural consultants on the
Lockheed team. The sixth platform, the sphere, was designed in PC and steel by
Tuned Sphere International.

Based upon data developed, the concrete versions of the OTEC platform system have
been developed by TYLI, with consultation and input by the respective naval
architects and LMSC.

During the course of study, several pertinent points were presented and discussed,
such as the state-of-the-art assessment of the concrete structure for OTEC; the
design, construction, and installation of the cold water pipe; and the review of the
Tuned Sphere Platform.

Effort has been made to develop conceptual prestressed concrete hull designs for the
six OTEC platforms, to the extent that preliminary cost estimation can be made for
each platform. The cost estimates for concrete hulls are presented in Table 2-80.

2.4.8.1 Design Consideration in Concrete. The first point to consider is that the
hull configuration of a sea structure is very much related to the material with which
it is to be built. The use of steel, for instance, would better permit an irregular
structural form such as a ship-shaped vessel. On the other hand, a platform with
concrete in mind would tend to assume simpler and bolder shapes, e.g., rectangular
and cylindrical configurations, that lend themselves better to the application of this
material.

The first essential is good quality concrete and the consistency of such good quality
concrete. Technologically, there is really no gap in the present status for making
high quality concrete, but certain safeguards are necessary to ensure that such high

Table 2-80

OTEC COST ANALYSIS – FIRST UNIT BASIS

Item	Price per cu yd $	Circular Barge		Internal Spar		Submersible		Ship		Semisubmersible		Sphere	
		Volume (cu yd)	Price ($1000)	Volume (cu yd)	Price ($1000)	Volume (cu yd)	Price ($1000)	Volume (cu yd)	Price ($1000)	Volume (cu yd)	Price ($1000)	Volume (cu yd)	Price ($1000)
Shell P.I.P.	1,090	–	–	26,824	29,238	6,540	7,129	–	–	–	–	41,697	45,449
Shell P.C.	750	9,251	6,938	50,286	37,715	14,333	10,750	14,671	11,003	10,960	8,220	–	–
Walls	750	40,277	30,208	29,754	22,316	50,171	37,628	50,652	37,989	50,590	37,941	23,395	17,546
Deck	750	16,971	12,728	33,286	24,965	12,196	9,147	19,561	14,671	28,739	21,554	34,446	25,834
Columns Stability-Columns	1,090	–	–	1,687	1,839	1,076	1,173	–	–	16,706	18,494	1,915	2,087
Total		66,499	49,874	141,837	116,073	84,316	65,827	84,884	63,663	106,995	86,209	101,453	90,916
Cold Water Pipe	1,000	For all Alternatives 28,000 cu yd, $28,000,000											
Total ($M)			77.9		144.1		93.8		91.7		114.2		118.9

quality concrete would be produced for the entire structure involving perhaps some 100,000 cu yds of concrete. The safeguards are primarily concerned with the choice of the proper material for the concrete, and the implementation of a rigid quality control program of delivering and placing good quality concrete throughout construction.

For the North Sea platforms, the performance of concrete has been excellent so far. No maintenance has been required. Inspections show the platforms to be in very good condition. There was some algae load, especially on prestressed concrete, as expected. Hence, it is now almost a universally established fact that concrete lasts very well at sea if the quality of concrete is properly controlled during production.

We are well acquainted with the fatigue strength of concrete. Prof. T. Y. Lin has personally conducted tests of the fatigue strength of prestressed concrete members up to 4 million cycles in Belgium. The results are excellent. With respect to the fatigue strength of prestressed concrete at sea, there is little recorded experience to date, simply because of the fact that large scale use of concrete at sea has only been a recent event. However, we have data for submerged concrete vessels, such as the "S. S. Selma", which show the concrete having essentially no damage after long submersion at sea and presumably under repetitive tidal load. Therefore, it can be expected that the fatigue strength of concrete should also be excellent at sea.

2.4.3.2 Construction. The method used so far in the North Sea, particularly Norway, in the construction of concrete platforms has been to build the lower portion of the platform in a shallow graving dock, then float it out to a deep wet dock for further construction and completion. Slipform is used extensively. This Norway method would be the simplest construction method, especially if graving dock and deep dock facilities are available. The situation in the United States is vastly different. There is hardly any sheltered water with sufficient depth for building concrete platform in the manner it was built in Norway.

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The technology gap here is primarily to find a way to construct the concrete platform with the facilities available in the United States, e.g., Puget Sound area. Tentatively, one might assume that facilities are available in the United States to provide a maximum floatout draft of 30 ft, and a maximum deep dock water depth of some 30 ft.

The tasks at hand would be (1) to make a survey of all available facilities around the U. S. for the establishment of the above construction constraints, and (2) to design the platform and hull configuration to satisfy these constraints. The Norway method would probably be the most economical construction method for the construction of a small number of sea structures. If the number of vessels to be built is large, it would overstrain available facilities and justify higher capital investment in plant, method, and equipment, to achieve better and more economical results. One strong possibility is the use of a construction cum launch barge. The sea structure is constructed on the barge which is tied up at some suitable point on the coast. When the structure is completed, the barge, with the structure on board, is towed to site by tugs, submerged by ballasting until it is detached from the self-floating structure, moved aside to clear the structure, refloated, and towed back to shore for re-use. The biggest advantage of the barge method is the freedom in the choice of a construction site, and of as many construction sites as required. It will also simplify and speed up construction procedure with the one-step handling of the structure before actual placement, and with the construction of the structure entirely in the dry. Design by this method represents, however, a gap in SOA technology, and requires further work.

CWP Construction. Several options are open, all of which represent to various degrees an advance on the SOA technology in constructing offshore structures. The promising ones are as follows:

(1) Onshore Construction and Launch Method. The CWP is constructed complete with ballasting arrangement on a gently sloping beach, possibly by prestressing together short precast segments. With both ends temporarily closed, the completed CWP is slowly rolled down the beach to float in the water. It is then towed to site, upended by ballasting, and moved into the center well position and secured. The

end bulkheads and ballast compartments are removed, and the CWP is ready for operation.

The serious problem areas associated with this method are:

(a) Positive control in launching and floating the CWP evenly along its length to avoid causing excessive transverse and longitudinal stresses

(b) Controlling the towing of a 3,000-ft-long vessel in open sea, and ensuring that design conditions are not exceeded

(c) Upending and installing operations, which are ahead of the SOA.

For platforms without a direct access to the center well, the CWP will have to be given a negative buoyancy to bring it under the control of barge cranes. It is then maneuvered beneath and across the vessel to the center well, raised to predetermined level to be locked into place. This method poses many problems. Two major ones are:

(a) A massive unit such as the CWP can be unmanageable at near equilibrium position during lowering. There are too many imponderables against this method for it to be accepted with the same confidence as the next method described below. E.g., these include the change of water densities with depth due to different salinity, temperature, and silt content; the change of weight due to water penetration; and the behavior of the long CWP under subsurface currents in horizontal and vertical directions. A small difference in the above factors can mean a weight change of hundreds of tons for a massive structure, and serious anxieties for the installation crew on the control barges.

(b) The hitching of the CWP which is subjected to uncontrollable motion to the platform, which has its own uncontrollable motions. It will be exceedingly difficult to design a hitching arrangement with the necessary tolerances for these motions, which will also perform well during normal operation.

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(2) <u>On-Site Assembly Method</u>. This method consists of building and transporting to the platform on site prefabricated segments of the CWP, which are as large as can be handled by the equipment used. The sections are picked up by heavy cranes on board the platform, placed in position over the completed section below, and joined to it by post-tensioned tendons. When jointing is completed, it is lowered into the water by jacks mounted around the center well to the position to receive the next segment. This method is considered closer to SOA than the previous method, although problems still abound if to a lesser degree.

(3) <u>Variation of Onshore Construction and Launch Method</u>. The long CWP may be made up in convenient lengths onshore, launched into water, and assembled afloat into the complete pipe by longitudinal prestressing. The joints may be made rigid by pressure grouting with underwater epoxy mortar, or given some flexibility by separating the segments at the joint with elastic materials, such as Neoprene.

This variation has the advantage of making up the CWP first in manageable lengths. This advantage may be more than offset by (a) the need to make every segment self-floating, and (b) the greatly magnified problem of matching and temporarily locking the segments together in water for longitudinal prestressing. Some of these difficulties could be reduced by assembling the segments progressively by adding one segment at a time to the pipe being assembled. It is nevertheless necessary to match one segment to the other by a positive matching device and securing the segments in the matched position long enough to enable stressing and grouting to be carried out.

2.4.8.3 <u>Conceptual Concrete Hull Designs and Cost</u>. System drawings showing the arrangement of power modules and piping configurations were furnished by the naval architects to T. Y. Lin International. Based upon this given information, the concrete designs were commenced. The proportioning of the concrete structures has been carried out by examining the critical sections within a given platform.

The unit costs have been arrived at jointly by LMSC and T.Y. Lin International. Note that in the table of cost analysis, the cold water pipe has been singled out, not only because it is a constant element common to all the platforms, but also because its cost is quite substantial as compared to the hull proper; thus, it would obscure the various concrete hull costs if it were to be considered integrally. It should also be noted that the cost figures are based on the data of similar past constructions and adopting them to the U. S. working conditions. It has been assumed that the graving basin method will be used. The cost presently shown does not include towing, nor installation of the cold water pipe. The cost of each platform as estimated can be expected to vary ±15%. One of the main purposes of the present cost analysis is to provide data on the relative basis for comparison for each of the concrete hulls under consideration.

2.5 OPTIMUM PLANT SYSTEM FOR NEW ORLEANS SITE

The optimum OTEC commercial plant system for the conditions of the site located off-shore New Orleans is presented in this section. This comparative assessment of several platform types is based primarily on the specified, baseline power system which is internally mounted to the hull. To further narrow the breadth of the evaluation, the primary assessment is based upon horizontally mounted shell-and-tube heat exchangers. A later section (Section 3) presents a similar assessment for the other four potential sites. Section 4 examines the improvements that are available in the plant when advanced power or ocean system components are interjected into the definition of the plant.

The methodology applied to the process of evaluating the platforms is presented in Section 2.5.2.1. The cost base for the six platform types and two materials is developed and presented in the following sections.

2.5.1 Plant Costs

This section presents a summary of the costs associated with constructing and de-
ploying OTEC plants at the New Orleans site.   Section 2.5.1.1 discusses cost
estimates for plants of 100-MW(e) output using the baseline power system; Section
2.5.1.2 presents cost projections for 200- and 500-MW(e) plants; and Section 2.5.1.3
compares the cost of the LMSC baseline OTEC platform design with that of a 265-MW(e)
version of the concrete spar with detachable power modules designed in the course of
this study.

It should be stressed that the cost estimates presented in this section are intended to
apply to commercial OTEC plants rather than to prototype units. Consequently, no
estimates are presented for the cost of facilities dedicated to OTEC plant construction;
rather, these facilities are assumed to exist and to be available.

2.5.1.1 100-MW(e) Plant Capital Costs. The capital costs of the ocean systems com-
ponents of an OTEC power plant can be readily broken down into the following categories:

- Platform hull and structures
- Cold water pipe
- Seawater pumps and ducting
- Position control systems
- Auxiliary systems
- Outfit and furnishings
- Deployment and CWP assembly

The costs of steel-hulled platforms were estimated separately by the appropriate naval
architect subcontractors, using the following common set of unit costs, expressed in
cnd-1977 dollars:

COSTS OF STEEL-HULLED PLATFORMS

Type of Structure	$/MT	or	$/LT
Hull	3,100		(3,150)
Colums	4,300		(4,369)
Superstructure	2,600		(2,642)

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The specific costs listed above represent a consensus of the naval architects' recent experience, projected to end-1977 dollar values. They include allowances for contingency, home office and engineering, and contractor's fee. In the process of cost estimation, these unit costs were first applied to the various components of each platform. The resulting cost components were then multiplied by factors to account for the complexity of the construction procedures employed. These complexity factors are listed in the table below.

COST FACTORS FOR CONSTRUCTION COMPLEXITY

Site of Construction	Approximate Drafts	Construction Cost Factor
Graving Dock	0 to 6.7 m (22 ft)	1.0
Shore Site (at Shipyard)	6.7 m to 9-12 m (30 to 40 ft)	1.25
Protected Shallow Water	9 m to 25 m (80 ft)	2
Unprotected Water	25 m and greater	3

Finally, the naval architecture subcontractors also estimated the cost of the various auxiliary systems and platform outfitting. For the sake of comparability, LMSC has adjusted all estimates to put them on a common basis. These adjustments are as follows:

- All concrete ballast costs have been re-estimated on the basis of a unit cost of $200/m^3 ($150/yd^3).
- Power system installation costs were excluded, as they are considered to be part of power system costs, rather than of platform costs.
- Estimates for auxiliary systems and outfitting of the circular barge, submersible, and tuned sphere configurations were re-estimated on the basis of the estimated cost for the ship, semisubmersible, and spar configuration.

The costs of all concrete-hulled platforms, as well as that of the concrete cold water pipe, were estimated by T.Y. Lin International. Based on previous experience of marine structures extrapolated to current U.S. Gulf and West Cost conditions, the following unit costs were employed:

COSTS OF CONCRETE-HULLED PLATFORMS

Current U.S. Gulf and West Coast	1st Unit	Follow-on Units
Hull	$980/m^3 ($750/yd^3)	$850/m^3 ($650/yd^3)
Columns	$1361/m^3 ($1040/yd^3)	$1177/m^3 ($900/yd^3)
Superstructure	$824/m^3 ($630/yd^3)	$720/m^3 ($550/yd^3)

All costs presented in this section are based on the second set of unit costs (follow-on units), since they are intended to represent the cost of commercial OTEC plants. It should be noted that concrete construction costs are expected to be 5 to 10 percent higher on the East Coast than on the Gulf or West Coasts.

LMSC has estimated separately the costs of the seawater and position control systems and of platform deployment and cold water pipe installation. A nominal baseline cold water pipe cost is used here. Detailed discussions of these cost items can be found in Sections 2.3 and 2.3.4 of this report.

The total costs of all configurations for a 100-MW(e) net output of the baseline power system are summarized for comparison in Tables 2-81 through 2-87; Table 2-88 presents those costs in terms of dollars per kilowatt net output. It will be noted that the cost of all platform configurations is significantly smaller for concrete than for steel designs. In addition, the relative cost ranking of the various configurations is altered by changing the construction materials. The ship is by far the lowest cost steel platforms, followed by the Tuned Sphere and the spar with detachable modules, while the barge and submersible are the lowest cost concrete configurations. Three concrete platforms – ship, barge, and submersible – fall in relatively narrow cost range between 185 and 200 million dollars; the remaining three configurations are 10 to 20 percent more costly. These comparisons apply for the baseline power at 100-MW(e) net output. Reductions in these platform costs are projected to be obtained by careful integration with the power system alternatives, by refinement of the requirements on the platform, and by further optimization of seawater system components, specifically the CWP and the seawater pumps. Sections 2.6 and 4 discuss in detail these reductions in platform costs.

Table 2-81

100-MW(e) OTEC PLATFORM CAPITAL COSTS ($M)

SHIP PLATFORM

SUBSYSTEM	HULL MATERIAL	
	STEEL	CONCRETE
HULL & STRUCTURE	125.4	55.2
COLD WATER PIPE	20.7	20.7
SEAWATER PUMPS & DUCTING	28.0	28.0
POSITION CONTROL SYSTEMS	27.5	27.5
AUXILIARY SYSTEMS	30.2	22.8
OUTFIT & FURNISHINGS	11.1	11.1
DEPLOYMENT & CWP ASSEMBLY/INSTALLATION	28.9	28.9
TOTAL	271.8	194.2

Table 2-81

100-MW(e) OTEC PLATFORM CAPITAL COSTS ($M)

CIRCULAR BARGE PLATFORM

SUBSYSTEM	HULL MATERIAL	
	STEEL	CONCRETE
HULL & STRUCTURE	206.1	43.2
COLD WATER PIPE	20.6	20.6
SEAWATER PUMPS & DUCTING	28.0	28.0
POSITION CONTROL SYSTEMS	32.9	32.9
AUXILIARY SYSTEMS	27.7	21.2
OUTFIT & FURNISHINGS	11.1	11.1
DEPLOYMENT & CWP ASSEMBLY/INSTALLATION	28.9	28.9
TOTAL	355.3	185.9

Table 2-82

100-MW(e) OTEC PLATFORM CAPITAL COSTS ($M)

SEMISUBMERSIBLE PLATFORM

SUBSYSTEM	HULL MATERIAL	
	STEEL	CONCRETE
HULL & STRUCTURE	216.4	74.0
COLD WATER PIPE	19.8	19.8
SEAWATER PUMPS & DUCTING	28.0	28.0
POSITION CONTROL SYSTEMS	38.4	38.4
AUXILIARY SYSTEMS	37.6	27.7
OUTFIT & FURNISHINGS	15.6	15.6
DEPLOYMENT & CWP ASSEMBLY/INSTALLATION	29.0	29.0
TOTAL	384.8	232.5

Table 2-84

100-MW(e) OTEC PLATFORM CAPITAL COSTS ($M)

SPHERE PLATFORM

SUBSYSTEM	HULL MATERIAL	
	STEEL	CONCRETE
HULL & STRUCTURE	155.1	76.9
COLD WATER PIPE	19.7	19.7
SEAWATER PUMPS & DUCTING	28.0	28.0
POSITION CONTROL SYSTEMS	33.3	33.3
AUXILIARY SYSTEMS	29.2	22.8
OUTFIT & FURNISHINGS	15.7	15.7
DEPLOYMENT & CWP ASSEMBLY/INSTALLATION	29.0	29.0
TOTAL	310.0	225.4

Table 2-85

100-MW(e) OTEC PLATFORM CAPITAL COSTS ($M)

SUBMERSIBLE PLATFORM

SUBSYSTEM	HULL MATERIAL	
	STEEL	CONCRETE
HULL & STRUCTURE	242.8	56.7
COLD WATER PIPE	19.8	19.8
SEAWATER PUMPS & DUCTING	28.0	28.0
POSITION CONTROL SYSTEMS	17.5	17.5
AUXILIARY SYSTEMS	34.2	24.7
OUTFIT & FURNISHINGS	15.7	15.7
DEPLOYMENT & CWP ASSEMBLY/INSTALLATION	29.0	29.0
TOTAL	387.0	191.4

Table 2-86

100-MW(e) OTEC PLATFORM CAPITAL COSTS ($M)

SPAR PLATFORM: INTERNAL POWER MODULES

SUBSYSTEM	HULL MATERIAL	
	STEEL	CONCRETE
HULL & STRUCTURE	304.3	100.2
COLD WATER PIPE	18.3	18.3
SEAWATER PUMPS & DUCTING	28.0	28.0
POSITION CONTROL SYSTEMS	22.5	22.5
AUXILIARY SYSTEMS	33.2	22.7
OUTFIT & FURNISHINGS	17.6	17.6
DEPLOYMENT & CWP ASSEMBLY/INSTALLATION	29.1	29.1
TOTAL	453.0	238.4

Table 2-87

100-MW(e) OTEC PLATFORM CAPITAL COSTS ($M)

SPAR PLATFORMS: DETACHABLE POWER MODULES

SUBSYSTEM	HULL MATERIAL	
	STEEL	CONCRETE
HULL & STRUCTURE	167.0	77.4
COLD WATER PIPE	18.3	18.3
SEAWATER PUMPS & DUCTING	28.0	28.0
POSITION CONTROL SYSTEMS	22.5	22.5
AUXILIARY SYSTEMS	33.2	22.7
OUTFIT & FURNISHINGS	17.6	17.6
DEPOLYMENT & CWP ASSEMBLY / INSTALLATION	29.1	29.1
TOTAL	315.7	215.6

Table 2-88

100-MW(e) OTEC PLATFORM CAPITAL COST SUMMARY [$/KW(e)]

CONFIGURATION	HULL MATERIAL	
	STEEL	CONCRETE
SHIP	2718	1942
BARGE	3553	1859
SEMISUBMERSIBLE	3848	2325
TUNED SPHERE	3100	2254
SUBMERSIBLE	3870	1914
SPAR		
- INTERNAL POWER MODULES	4530	2384
- DETACHABLE POWER MODULES	3157	2156

2.5.1.2 200- and 500-MW(e) Plant Capital Costs. LMSC has projected the cost of
building 200- and 500-MW(e) OTEC plants of the six basic configurations discussed in
this report. These costs, expressed in dollars per kilowatt of net output, are listed
in Tables 2-89 and 2-90, respectively. Comparing these unit costs with those
given in Table 2-88 for 100-MW(e) plants, it is apparent that OTEC platforms are
subject to significant economies of scale. As plant output is increased by a factor of
five, the unit cost of steel platforms decreases by approximately one quarter, and
that of concrete platforms by roughly one third. It should be stressed here that the
costs of platforms larger than 100-MW(e) were estimated on the assumption of power
system space requirements increasing linearly with net output. While this is correct
if 25-MW(e) power modules are the largest available, it would appear that platforms
designed to accommodate large individual power units might realize greater economies
of scale than indicated in this study, as a result of increased packing efficiency.

LMSC believes the comparative costs presented in this section for the baseline power
system can be reduced significantly through further integration, particularly with the
power system.

Table 2-89

200-MW(e) OTEC PLATFORM CAPITAL COST SUMMARY [$/KW(e)]

CONFIGURATION	HULL MATERIAL	
	STEEL	CONCRETE
SHIP	2386	1666
BARGE	3204	1532
SEMISUBMERSIBLE	3472	1957
TUNED SPHERE	2778	1882
SUBMERSIBLE	3522	1575
SPAR		
- INTERNAL POWER MODULES	3912	2045
- DETACHABLE POWER MODULES	2655	1816

Table 2-90

500-MW(e) OTEC PLATFORM CAPITAL COST SUMMARY [$/KW(e)]

CONFIGURATION	HULL MATERIAL	
	STEEL	CONCRETE
SHIP	2108	1405
BARGE	2916	1287
SEMISUBMERSIBLE	3136	1643
TUNED SPHERE	2452	1574
SUBMERSIBLE	3250	1322

SPAR
 	
  - INTERNAL POWER MODULES
  - DETACHABLE POWER MODULES
	
	3639
	2381
		
		1801
		1572

2.5.1.3 <u>Comparison Between LMSC Baseline and Concrete Spar With Detachable Power Modules.</u> The cost estimates presented in this report are substantially in excess of LMSC's expectations on the basis of earlier studies. To determine the cause of these discrepancies, the costs of LMSC's updated 265-MW (e) baseline configuration (OTEC Test Facilities Study Program, SAN/1156-77/1) have been compared with those of the concrete spar configuration with detachable power modules developed under this contract. To this effect, the costs of a 265-MW(e) concrete spar with detachable modules were estimated, on the assumption of a cold water pipe length of 600 m, roughly the same length of cold water pipe used in LMSC's baseline configuration. The dimensions and weights of power system components supplied by DOE were retained for the current spar configuration, although they are significantly different from those in LMSC's baseline design. It should be emphasized at the outset that the comparison that follows is less than fully valid, because the current configuration is at a preconceptual stage of development. Because the current configuration has neither been optimized nor fully integrated with a power system developed in conjunction with it, it is reasonable to expect that its costs would exceed in any case those of the LMSC baseline, which has benefited from such an iterative design optimization process in conjunction with the power system it houses.

Table 2-91 compares the various cost elements of the two platform designs. The estimate for the current design is roughly 50 percent higher than that for LMSC's baseline configuration. More than half of this difference is due to differences in hull structure costs, which in turn reflect differing material weights, as the same material unit costs have been used in developing both estimates. At least to some extent the greater material requirements of the current configuration appear to reflect the greater relative size of power system components used in this study.

The discrepancy in cold water pipe costs is due to its wall thickness being greater in the current study than in the original LMSC work (Ocean Thermal Energy Conversion (OTEC) Power Plant Technical and Economic Feasibility, NSF/RANN/SE/GI-C937/FR/75/1). The cost of seawater systems is more than twice as high in the current configuration as reported earlier by LMSC. Economies of scale are believed to account

Table 2-91

COMPARISON OF 265-MW(e) PLATFORM COSTS – $M

Component	LMSC Baseline Spar 265-MW(e) (Net)	OPCI Concrete Spar 265-MW(e) (Net)
Hull and Structure	103.3	198.8
Cold Water Pipe	21.1	37.0
Seawater Pumps and Ducting	29.8	66.3
Position Control Systems	44.3	36.0
Auxiliary Systems / Outfit and Furnishings	31.7	46.5
Deployment and CWP Assembly/ Installation	6.2	30.3
TOTAL	236.4	414.9

for a large fraction of the difference in pump costs. The seawater pumps contemplated in the LMSC baseline are roughly three times larger than those used in this study. According to information presented in "Deep Water Pipe, Pump, and Mooring Study; Ocean Thermal Energy Conversion Program" (C00-2642-3), this should reduce their cost by roughly 50 percent. .

Cost estimates for position control systems appear to be in reasonably good agreement for both platforms. The discrepancy in the costs given for auxiliary systems and outfit and furnishings, however, is quite significant, and may be due to an underestimate of these costs in the early Lockheed studies. Finally, the enormous increase in deployment costs is almost entirely due to the method adopted for at-sea cold water pipe installation. It will be remembered that LMSC's baseline telescopic cold water pipe was to be built inside the platform hull in a nested position; deployment would then involve no more than simple extension of the telescopic pipe. Unfortunately, adoption of a much longer pipe in the present study dictated the abandonment of this simple deployment concept; deployment is now assumed to take place as discussed in Section 2.3.3.1. Of course, further study will almost certainly result in an improved deployment procedure.

The last point discussed above highlights an important caveat to the cost estimates presented in this report. They represent the costs associated with first-order solutions to design requirements. As such, they are likely to overestimate the costs associated with final solutions, which will benefit from continuous design optimization and closer integration with power system component design concepts.

2.5.2 System Optimization

The process utilized in deriving the most satisfactory plant system for the New Orleans
site is an adaptation of the Kepner-Tregoe Associates (KTA) procedure for decision
analysis. This process is described and defined for this application in the next section.

2.5.2.1 Methodology of Evaluation Process. The evaluation of the most satisfactory
configurations of the platform for the OTEC Commercial Plant will be based upon the
data as described in the preceeding section and the evaluation criteria which are des-
cribed in this section. The actual evaluation will utilize the Kepner-Tregoe Associates
procedure for decision analysis. The procedure involves the following:

1. Formulation of an objective decision statement.

2. Preparation of a set of objectives which MUST be satisfied and all other
    objectives (which are termed WANTS since they are desirable but are not
    mandatory).

3. Establishment of weighting factors reflecting the relative importance of the
    wants.

4. Evaluation of comparative performance of the six configurations for each
    WANT.

5. Assessment of possible adverse consequences.

6. Comparison of total evaluation of WANTS with possible adverse consequences.

The objectives and criteria formulated for the New Orleans site are presented in the
subsequent pages.

MUST #1 (Meet all general platform requirements) requires that the primary
OTEC design and performance requirements be applied for all platform configu-
rations that are being evaluated. The specific requirements, which vary among
the several mission/site combinations, are presented as the MUSTS on the
Decision Analysis Worksheets.

Decision Statement ➤ IDENTIFY THE MOST SATISFACTORY OTEC PLATFORM CONFIGURATIONS WITH THE BEST PROSPECT OF COMMERCIAL VIABILITY FOR ELECTRICAL TRANSMISSION FOR LOW CURRENT SITES.

Decision Analysis Worksheet

ALTERNATIVES

OBJECTIVES

MUST (*absolutely essential for the decision to be successful?*)

1. Meet all general platform requirements
2. Survive extreme environments as specified
3. Operate in typical 1.2 knot surface current
4. Assure continuous electrical connection to riser

WANT (*Desirable objectives but not absolutely essential to the success of the decision chosen*)

OBJECTIVES	WT	A INFO	SC	WT	B INFO	SC	WT	C INFO	SC	WT	D INFO	SC	WT
1. Low initial capital cost per KW	10												
2. Least impact on CMP requirements	6												
3. Acceptability for maintenance, repair and replace	5												
4. Flexibility of platform type to accommodate various arrangements and sizes of power system components	5												
5. Least potential for motion degradation of power availability	3												
6. Minimum amount of extension of SOTA	2												
7. Shortest schedule for construction	2												
8. Shortest schedule for deployment	2												
9. Minimum adverse effects of site variations	2												
10. Potential for acceptability by commercial users	2												
11. Minimum energy required to construct	1												
	40												

TOTAL WT SC ▶

TOTAL ADVERSE CONSEQUENCES SC (RISK FACTOR)

COMPARE AND CHOOSE BEST BALANCED ALTERNATIVE

MUST #2 (Survive extreme environments as specified) deals with the ability of a candidate to survive the extreme environment specified in the environmental description. Obviously, a platform that will not meet the envelope of conditions experienced at the various specified sites is not acceptable. All the platform candidates will be designed to survive hurricane conditions.

MUST #3 (Operate in 1. 2 (or 4. 7) knot surface current) requires the platform candidates to be optimized for operation at specific current conditions.

MUST #4 (Assure continuous electrical connection to riser) requires that riser for the electrical transmission mission remain connected, even during the 100-year storm. This requirement does not apply during planned maintenance, repair, or replacement operations of the electrical riser system.

All platform configurations will be designed to satisfy these specific MUSTS and the general OTEC system requirements. The resulting platforms will have properties, performance, and costs for which the desired objectives are the WANTS as shown on the Decision Analysis worksheets. These wants consider key parameters of commercial viability, development risk, acceptability, flexibility, convenience, and the energy cost of the platform in this order of importance.

WANT #1 (Low initial capital cost per kW) considers minimal initial cost for a given power output. The material, construction, and deployment costs are included. CWP costs are estimated for each configuration.

WANT #2 (Least impact on CWP requirements) recognizes that the CWP is the major technical challenge for platform development. The less stringent the requirements that are imposed on the CWP, the lower will be the cost, schedule, deployment, and risks.

WANT #3 (Accessibility for maintenance and repair) returns to the problem of platform internal geometry, in considering the ease with which on-site maintenance can be performed. A design with relatively unreachable external or submerged components will receive a small penalty.

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WANT #4 (Flexibility of platform type to accommodate various arrangements and sizes of power system components) addresses the fact that this is a developing technology and that the precise power plants to be potentially incorporated can not now be fully determined. Future evolutionary developments may require various arrangements. This WANT will penalize candidates with relatively inflexible internal geometry or poor arrangements for external modules.

WANT #5 (Least potential for motion degradation of power availability) favors the design that is least susceptible to sea motions which impair output of the power system. This accounts for maximum optimization of power systems which results from reduced motion characteristics.

WANT #6 (Minimum amount of extension of the SOTA) favors a solution for the commercial plant which has minimum technical risk. Advances that are essential to commercial viability will be critically judged by this WANT as compared with platform reliability and costs.

WANT #7 (Shortest schedule for construction) relates to the lack of output for the commercial plant during the construction period. In addition, the larger a construction span the more likely are further delays and/or changes in the economic situation, which are forms of program risk.

WANT #8 (Shortest schedule for deployment) relates to the same factors as in WANT #7 and to the additional concern that extended period of on-site work will cause greater risks for unplanned delays resulting from weather interruptions.

WANT #9 (Minimum adverse effects of site variations) is concerned with the potential for universality of the chosen platform candidate. Both in design and construction, it is cost-effective to have a platform which requires little or no tailoring or new development to meet the conditions of a specific site.

WANT #10 (Potential acceptability of configuration by commercial users) considers all the platform characteristics that affect the scaling to a commercially acceptable solution as well as the subjective judgments against innovation. The comments of potential commercial operators will be solicited in this connection.

WANT #11 (Minimum energy required to construct) It is obviously desirable to make this net energy as large as possible in the platform for the commercial plant.

Many of these factors have already considered elements of potential risk and have costed/scheduled/planned alternatives to reasonable engineering practice. As an overall assessment of risk the possible adverse consequences for each configuration will be developed and qualified using the checklist presented below. The schedule, technical, and performance risks have been evaluated by this process.

Checklist of Possible Adverse Consequences

- Platform motions have potential to significantly reduce output
- Platform motions incapacitate personnel
- Complexity of platform/CWP interface
- Configuration implies risk to personnel
- Construction schedule longer than planned
- Initial costs greater than planned
- Technology advances lagging requirements

2.5.2.2 Evaluation of Comparative Performance. Each desirable objective (WANT) for the OTEC commercial plant has been evaluated comparatively among the six types of platforms and the detachable module for the spar. The following tables present all the data and considerations that have been used in the comparative evaluation process. This comparison is based on 100 MW(e) net output plants. Subsequent evaluations deal with other plant outputs and potential advances in the technology.

- EACH PLATFORM MUST (AND DOES):
  - MEET ALL GENERAL PLATFORM REQUIREMENTS
  - SURVIVE SPECIFIED EXTREME ENVIRONMENTS
  - OPERATE IN SPECIFIED CURRENTS
  - ASSURE CONTINUOUS ELECTRICAL CONNECTION
- PLATFORM SELECTION BASED ON DIFFERENCES IN ACHIEVING WANTS:

|	FACTOR	WEIGHT
- LOW CAPITAL COST	COST	10
- LOW IMPACT ON CWP REQUIREMENTS	TECHNICAL FEASIBILITY	6
- ACCESSIBILITY	OPERABILITY	5
- FLEXIBILITY	OPERABILITY	5
- LOW MOTIONS	OPERABILITY	3
- MINIMUM TECHNICAL ADVANCE	TECHNICAL FEASIBILITY	2
- SHORTEST SCHEDULE FOR CONSTRUCTION	SCHEDULE	2
- SHORTEST SCHEDULE FOR DEPLOYMENT	SCHEDULE/RISK	2
- LOW SITE SENSITIVITY	COST	2
- ACCEPTABILITY FOR COMMERCIAL USE	TECHNICAL FEASIBILITY	2
- MINIMUM CONSTRUCTION ENERGY USE	TECHNICAL FEASIBILITY	1

LOW CAPITAL COST PER KW(e)

	STEEL				CONCRETE			
	$/KW(e)	$/$ LOW	RANK	SCORE	$/KW(e)	$/$ LOW	RANK	SCORE
SHIP	2,981 LOW	1.000	1	10	2,205	1.088	4	9
BARGE	3,720	1.248	4	8	2,026 LOW	1.000	1	10
SEMI	3,956	1.330	5	8	2,443	1.206	6	8
TUNED SPHERE	3,295	1.105	3	9	2,449	1.209	7	8
SUB	4,040	1.355	6	7	2,084	1.028	2	10
SPAR ⎰ INTERNAL	4,543	1.523	7	5	2,397	1.183	5	8
SPAR ⎱ DETACHED	3,170	1.063	2	9	2,169	1.071	3	9

SCORE = 10/$/$ LOW

LOW CAPITAL COST PER KW(e)

STEEL

CONCRETE

- NEW ORLEANS
- 100-MW(e) NET
- BASELINE POWER SYSTEM
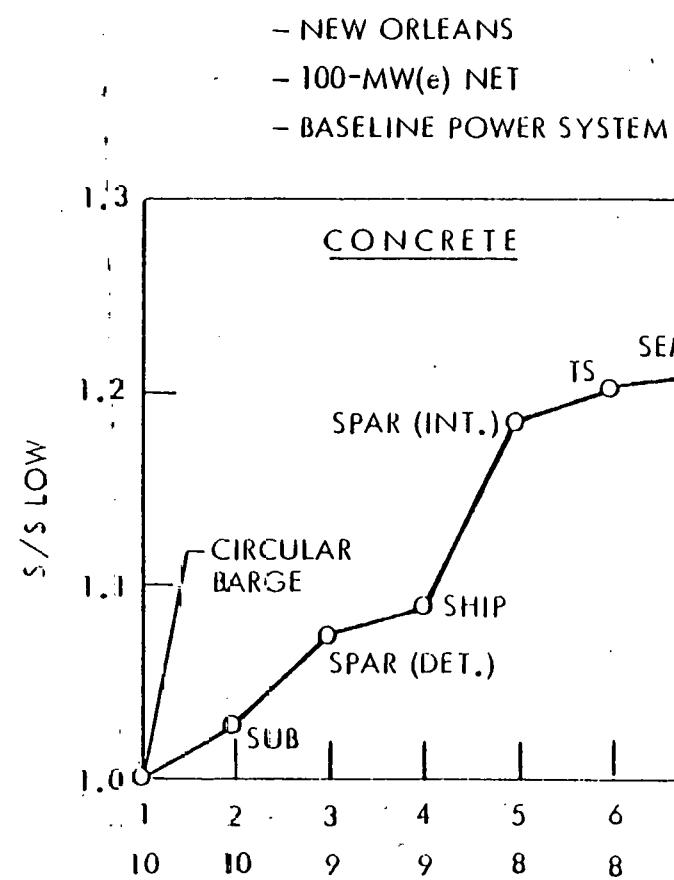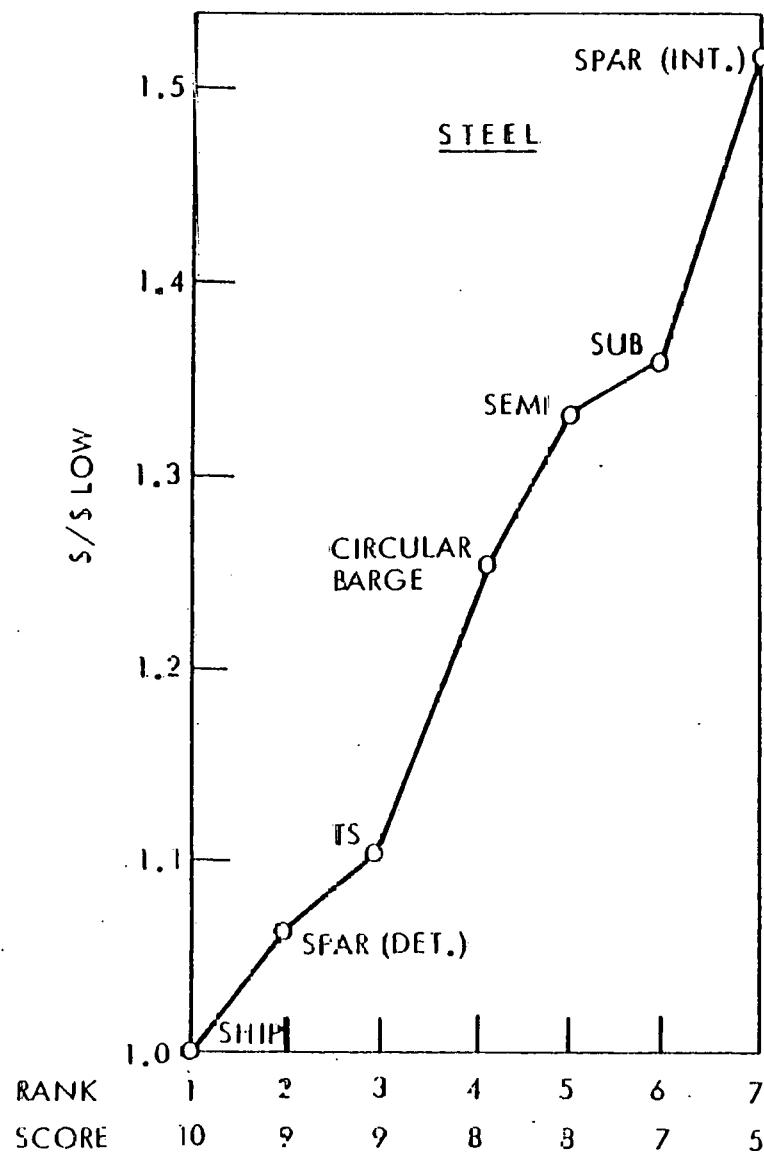
LEAST IMPACT ON CWP REQUIREMENTS

	MAX. SIGNIFICANT AMP-LITUDE OF DYNAMIC BENDING MOMENT IN HURRICANE LB-FT	$\frac{BM}{BM_L}$	RANKING	SCORE
SHIP	1.21×10^9	2.327	7	4
CIRCULAR BARGE	0.96	1.846	5	5
SEMI	0.81	1.558	3	6
TUNED SPHERE	1.01	1.942	6	5
SUB	0.95	1.827	4	5
SPAR - INT.	0.52*LOW	1.000	2	10
- DET.	0.52*LOW	1.000	1	10

*HIGH ATTACHMENT POINT

$$SCORE = \frac{10}{\frac{BM}{BM_{LOW}}}$$
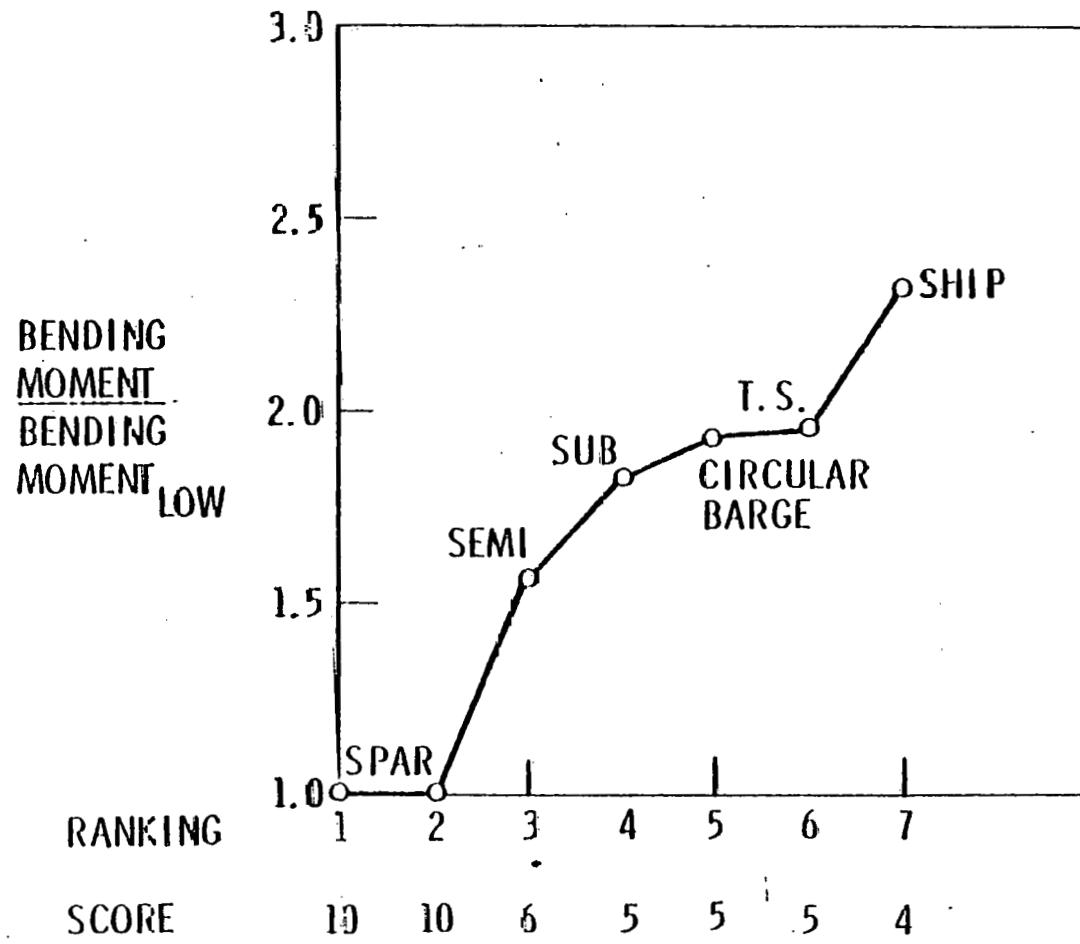
ACCESSIBILITY FOR MAINTENANCE,
REPAIR, AND REPLACEMENT

	SPACE AROUND P.S.	HEAT EXCHANGER LIFT ACCESS	IMPACT ON OPERATIONS	SUM	RANK	SCORE
SHIP	+	+	+	3+	1	10
CIRCULAR BARGE	+	+	+	3+	1	10
SEMI	+	-	-	-1	3	3
TUNED SPHERE	+	-	0	0	2	5
SUB	0	-	-	-2	4	1
SPAR - INT.	+	-	-	-1	3	3
- DET.	-	0	+	0	2	5

SPACE AROUND
POWER SYSTEM

+ = GOOD
0 = ADEQUATE
- = POOR

HEAT EXCHANGER
LIFT ACCESS

+ = DIRECT
0 = CONVENIENT
- = COMPLEX

IMPACT ON OPERATIONS
DURING HEAT EXCHANGER REMOVAL

+ = CONTINUE AT FULL CAPACITY
0 = CURTAILED OUTPUT
- = SUSPENDED OPERATIONS

FLEXIBILITY FOR ARRANGEMENTS OF POWER SYSTEM

	HORIZONTAL & VERTICAL HX	LARGER HX	SMALLER HX	SUM	RANK	SCORE
SHIP	-	+	+	+1	3	4
CIRCULAR BARGE	-	+	+	+1	3	4
SEMI	0	0	+	+1	3	4
TUNED SPHERE	+	0	+	+2	2	7
SUB	0	0	+	+1	3	4
SPAR - INT.	+	+	+	+3	1	10
DET.	+	+	+	+3	1	10

SUM OF
QUALITIES

RANK	1	1	2	3	3	3	3
SCORE	10	10	7	4	4	4	4
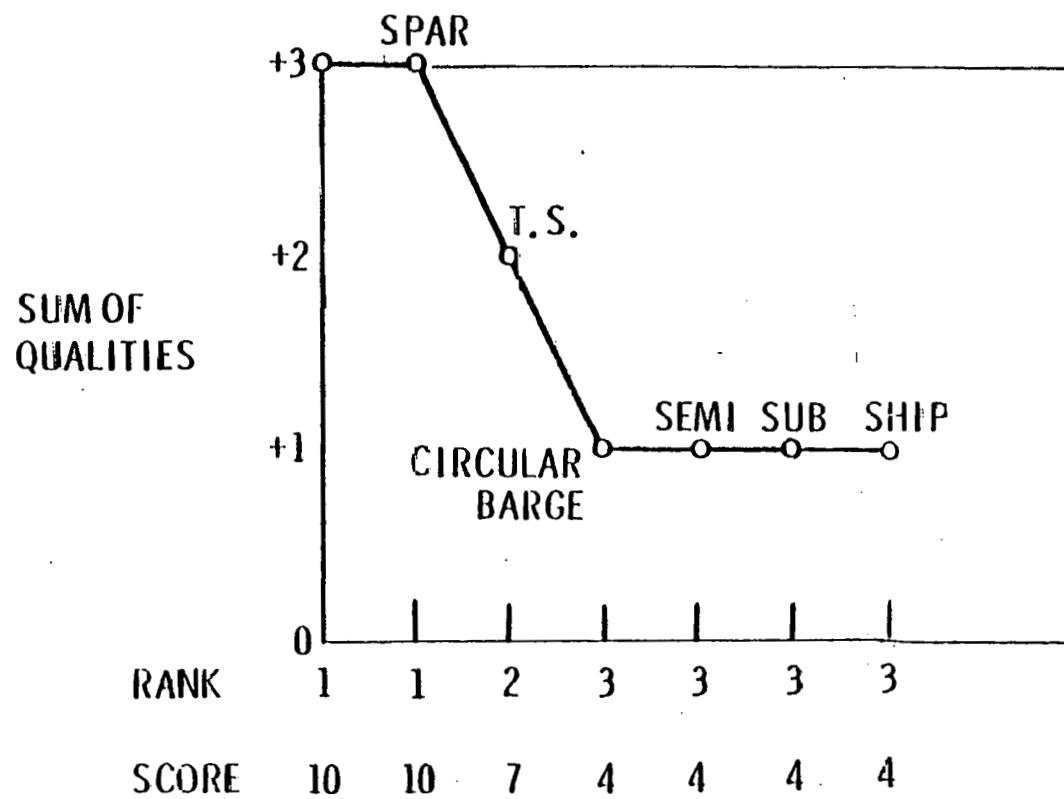
LEAST POTENTIAL DEGRADATION
OF POWER AVAILABILITY

LEAST	SHIP	BARGE	SEMI	TUNED SPHERE	SUB	SPAR
MAX. HEAVE MOTION	5	5	8	9	10	9
CENTER HEAVE MOTION	5	4	8	10	9	9
PITCH MOTION	6	4	8	8	9	10
ROLL MOTION	2	4	8	8	6	10
SURGE MOTION	4	6	8	7	9	10
SUM OF MOTIONS	22	23	40	42	42	48
RANKING	6	5	4	3	2	1
SCORE	2	2	6	7	8	10
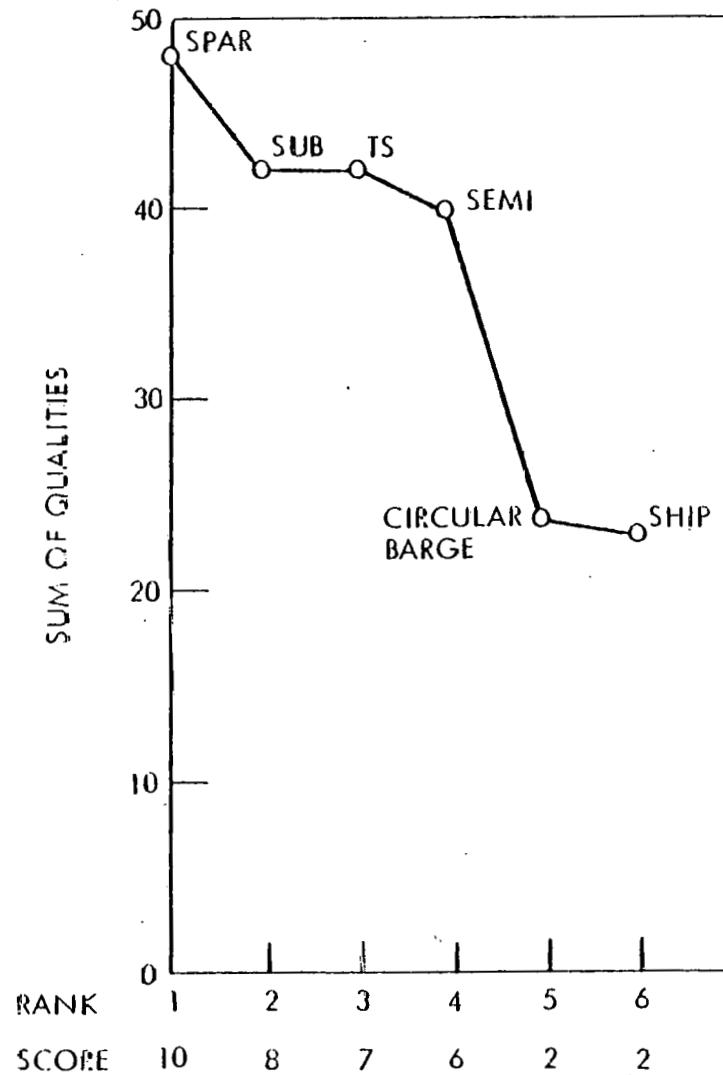
	SHIP	BARGE	SEMI	TUNED SPHERE	SUB	SPAR$_{INT}$	SPAR$_{DET}$
CONCRETE CONSTRUCTABILITY	+	0	0	-	+	0	-
STEEL-ERECTION COMPLEXITY FACTOR	+	+	0	-	-	0	0
SUM OF QUALITIES	+2	+1	0	-2	0	0	-1
RANKING	1	2	3	4	3	3	4
SCORE	10	8	6	2	6	6	4

SHIP

+2

+1 — CIRCULAR BARGE

SUM OF
QUALITIES

SUB   SPAR INT.

0

SEMI

-1 — SPAR DET.

TUNED
SPHERE

-2

RANK	1	1	2	2	3	3	4
SCORE	10	8	6	6	6	4	2
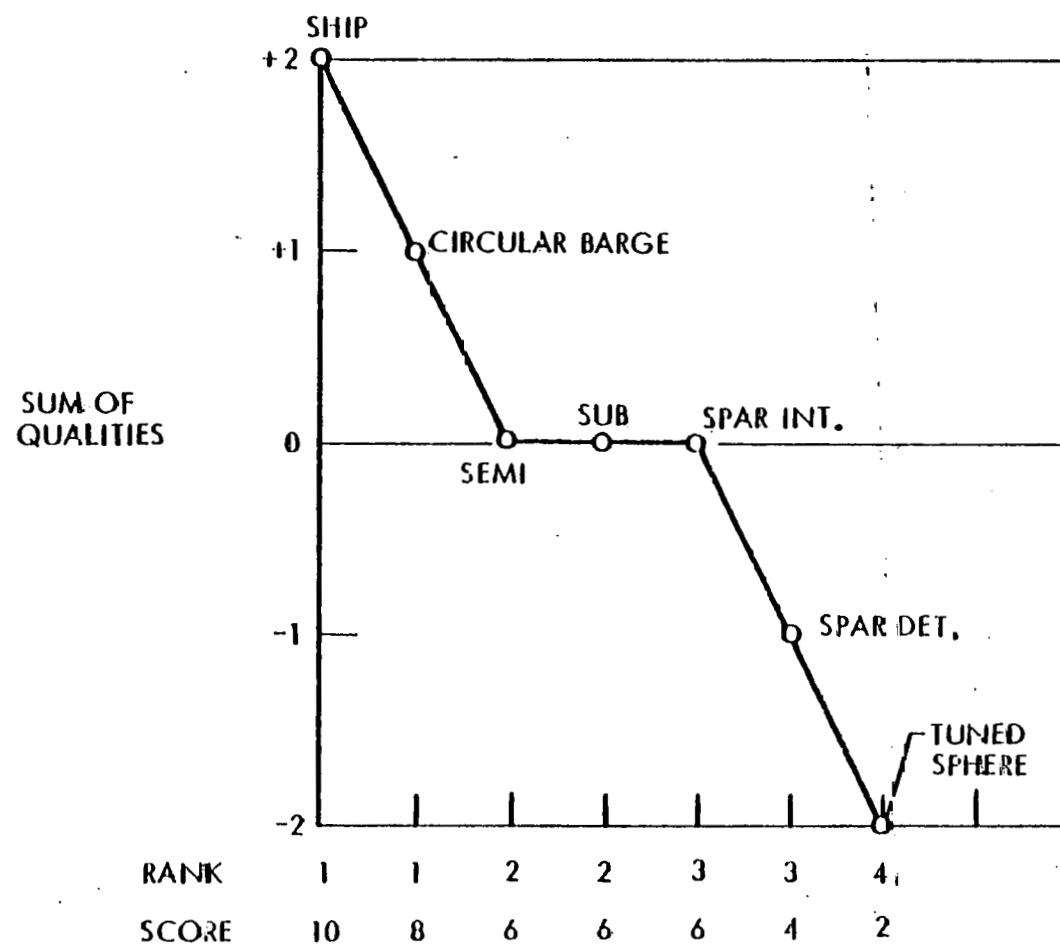
SHORTEST CONSTRUCTION SCHEDULE

RATIO OF VOLUME OF CONCRETE	RANK	SCORE
1.27	4	7
1.00	1	10
1.60	6	5
1.51	5	6
1.26	3	7
2.12	7	4
1.05	2	9

SHORTEST DEPLOYMENT SCHEDULE	SCORE
SHIP	10
BARGE	6
SEMI	6
T.S	2
SUB	3
SPAR INT	1
SPAR DET	1

MINIMUM NET ENERGY IS PROPORTIONAL TO INVERSE OF VOLUME OF CONCRETE

(USE SCORE FOR CONSTRUCTION SCHEDULE)

		SHIP	BARGE	SEMI	TUNED SPHERE	SUB	SPAR
LEAST SITE EFFECTS ON	1. CWP	4	5	6	5	5	10
	2. POSITION CONTROL	7	7	6	7	10	8
	3. MOTIONS	1	4	6	7	8	10
	4. DEPLOYMENT	10	5	4	2	3	1
SUM OF QUALITIES		22	21	22	21	26	29
RANKING		4	6	3	5	2	1
SCORE		6	1	7	4	8	10

PLATFORM RISK ASSESMENT

RISK	SHIP	CIRCULAR BARGE	SEMI	TUNED SPHERE	SUB	SPAR INT	SPAR DET
1. PLATFORM MOTION CAUSES CWP PROBLEMS	7/8 = 56	2/8 = 16	–	2/8 = 16	–	–	–
2. PLATFORM MOTION CAUSES POWER DEGRADATION	6/2 = 12	5/2 = 10	–	2/2 = 4	–	–	–
3. SURFACING OF SUBMERGED STRUCTURE FOR MAINTENANCE INCREASES CWP DESIGN NEEDS	–	–	5/2 = 10	5/3 = 15	7/5 = 35	4/4 = 16	–
4. CONSTRUCTABILITY	–	2/2 = 4	2/4 = 8	8/5 = 40	–	3/4 = 12	4/4 = 16
5. DOCKING AND SEALING OF DETACHABLE MODULES	–	–	–	–	–	–	6/3 = 18
TOTAL RISK FACTOR	68	30	18	75	35	28	34

RISK FACTOR = P x S   where P = Probability of occurence   shown as P/S = RF

S = Severity of impact

EVALUATION FOR OTEC PLATFORM-100 MW(e) (NET), NEW ORLEANS

WANTS / CONCRETE	WT	SHIP		CIRCULAR BARGE		SEMI		TUNED SPHERE		SUB		SPAR (INT)		SPAR (DET)	
		S	P	S	P	S	P	S	P	S	P	S	P	S	P
1. LOW INITIAL COST/KW	10	9	90	10	100	8	80	8	80	10	100	8	80	9	90
2. LEAST IMPACT ON CWP	6	4	24	5	30	6	36	5	30	5	30	10	60	10	60
3. ACCESSIBILITY FOR P.S.	5	10	50	10	50	3	15	5	25	1	5	3	15	5	25
4. FLEXIBILITY FOR P.S.	5	4	20	4	20	4	20	7	35	4	20	10	50	10	50
5. LEAST MOTION DEGRADING	3	2	6	2	6	6	18	7	21	8	24	10	30	10	30
6. MINIMUM EXTENSION OF SOTA	2	10	20	8	16	6	12	2	4	6	12	6	12	4	8
7. SHORTEST CONS. SCHEDULE	2	7	14	10	20	5	10	6	12	7	14	4	8	9	18
8. SHORTEST DEPLOYMENT SCHEDULE	2	10	20	6	12	6	12	2	4	3	6	1	2	1	2
9. MINIMUM ADVERSE SITE AFFECTS	2	6	12	1	2	7	14	4	8	8	16	10	20	10	20
10. ACCEPTABILITY	2														
11. MINIMUM NET ENERGY	1	7	7	10	10	5	5	6	6	7	7	4	4	9	9
SUBTOTAL (2-11)	30	173		166		142		145		134		201		222	
TOTAL	40	263		266		222		225		234		281		312	
RANK		4		3		7		6		5		2		1	

EVALUATION FOR OTEC PLATFORMS – 100-MW(e) (NET), NEW ORLEANS

LOCKHEED MISSILES & SPACE COMPANY. INC.
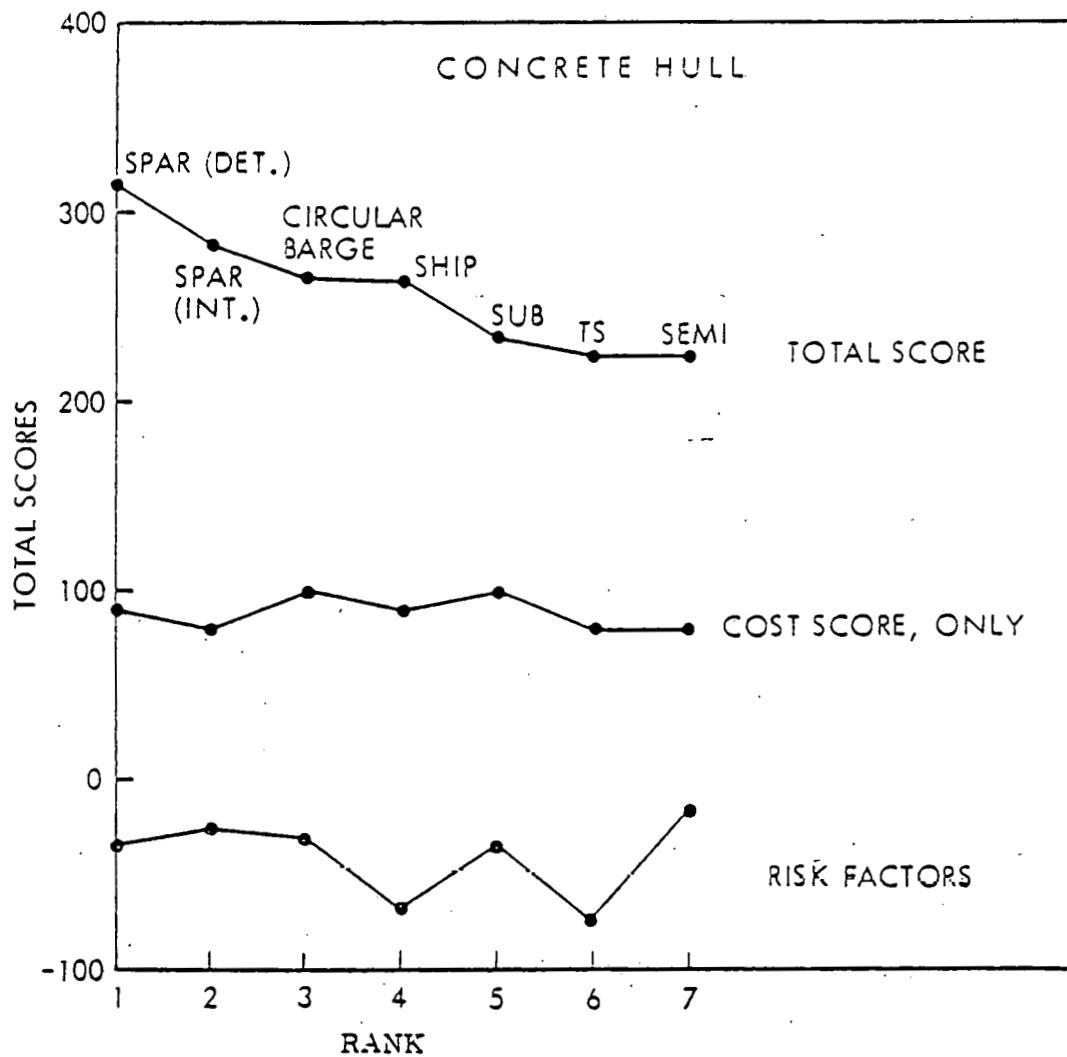
2.6 SENSITIVITY TO REQUIREMENTS

There are several requirements on the commercial OTEC plant which have an
impact on the platform and are not related to the platform or specific
features of the power system. The effect of these requirements is assessed
in this Section. The following Sections (3 and 4) present sensitivities to
site parameters and to system and subsystem characteristics. The requirements
considered here as the following

1. Construction of major components will be in U.S. facilities
2. Power system component layout will be within the hull
3. Continual operational ability of power cycle

2.6.1 Major Construction in U.S.

There is a potential cost savings if major components such as the platform
hull and cold water pipe were purchased from foreign facilities.

Several foreign countries offer shipyard construction costs significantly
lower than those found in the United States. The impact of foreign construc-
tion on OTEC platform cost has been evaluated. LMSC has available information
on foreign shipyard costs collected in the course of an earlier Independent
Development project. In particular, Japanese, Korean and Spanish shipyards'
costs appear to be 20% to 25% lower than American shipyards'. However, this
reduction in cost would apply only to platform hulls and to cold water pipes;
the cost of all other items, Tables 2-81 to 2-86, would most likely
remain unchanged. It is noted that hulls and cold water pipes account for
roughly 60% of the cost of steel platforms, but only for some 40% of the cost
of concrete units. Consequently, the cost reduction to be expected from
foreign construction of the platform and cold water pipe is of the order of
12% to 15% of total cost for steel platforms, and from 8% to 10% of total cost
for concrete units.

2.6.2 Power System Component Layout Within the Hull

As a means of reducing platform cost, LMSC investigated the possibility of

placing major power system components outside the hull, housed in self-contained, detachable modules. The effect of this arrangement on the costs of the spar platform configuration were discussed in Section 2.5.1. Platform hull cost decreased by nearly half for the steel structure, and by one quarter for the concrete unit. The total cost of the steel platform was reduced by over 30% and that of the concrete platform by nearly 10%. The magnitude of these reductions suggests that the detachable module alternative should be investigated seriously for all platforms which lend themselves to this approach of component layout. The optimization of power system components for a detachable module arrangement could also be expected to produce lower plant costs.

2.6.3 Continual Operational Ability of Power Cycle

LMSC believes that the mooring systems discussed in this report will be capable of meeting the watch circle requirements specified by DOE to accommodate a free, catenary, electrical riser system. Relaxing these requirements would be reflected in a decrease in mooring system costs, which account for roughly 5% to 10% of total steel platform cost, and 10% to 15% of concrete platform costs. While reductions in this cost item are thus unlikely to have a dramatic effect on overall platform costs, this is nonetheless a possible source of cost savings that should be investigated. Use of a single point moor would be a significant cost reduction. It would require, however, development of a electrically-connecting, mooring swivel. The net impact on the cost of the commercial plant must consider the potentially greater costs for the free, catenary riser for the electrical transmission system as the watch circle is increased.

Section 3
EFFECT OF SITE VARIATION ON OPTIMUM PLANT SYSTEM

This section summarizes the effects that site have on selection of and characteristics of an optimum plant or ocean system. In Section 3.1 these effects are expressed primarily in terms of cost and characteristic variations, and in Section 3.2 an optimum plant for each of the candidate sites is identified.

The site parameters that cause optimum choices and characteristics to vary with site include environmental and oceanographic characteristics such as weather, distance to port, current, and depth. These are summarized in Table 2-31. The ocean systems considered in this section are the seawater system, particularly the cold water pipe, and the position control system options — mooring and dynamic positioning. Also treated is the variability of seawater and position control systems with platform type where such consideration contributes to identification of an optimum plant. Design variations are not considered for the hull and support systems or for the power system.

3.1 OCEAN SYSTEM VARIATIONS BETWEEN SITES

The Ocean Systems principally affected by site — seawater and position keeping system — are treated in this section. Results discussed in Section 2 are summarized to illustrate system cost variation between candidate sites.

3.1.1 Seawater System

The cold water pipe is the component of the seawater system whose design and cost are most influenced by site variation. The baseline CWP design concept (Section 2.3.3.1) is dependent on site conditions of waves, current, and temperature profile, as well as on platform type.

The intensity of the 100-year storm determines, for a given platform, the extreme value of dynamic bending moment and stress in the pipe wall. This, in turn, may determine the required wall thickness over most of the pipe length. However, in a sample stress analysis of the CWP, the bending stress in the upper portion is less than the static tensile stress, indicating that a thinner pipe is adequate at least for portions of the pipe length. The lighter pipe would result in lower axial stress and lower bending stress since lower stiffness appears to reduce dynamic bending moment.

Costs of cold water pipes have been estimated for each platform type and several sea conditions, and are presented in Section 2.3.3.1. The various sites defined for this study are characterized by those extreme sea conditions. Hence, the effect of site on the cost of cold water pipes is shown in Section 2.3.3.1. Essentially the impact of site can be represented by a factor (relative to the New Orleans site) with the cost of CWP for each platform varying in relation to this factor as follows:

Site		CWP Cost Relative to New Orleans
New Orleans	H_S = 58.1 ft	1.00
Keahole Point, Hawaii	H_S = 35.9 ft	0.48
Puerto Rico	H_S = 44.2 ft	0.67
Key West	H_S = 45.8 ft	0.67

Platform	Approximate Relative Cost Among Platforms
Ship	2.40
Barge	1.90
Semi	1.60
Tuned Sphere	2.00
Submersible	1.88
Spar — Internal, deep attachment	2.17
— Detached, high attachment	1.00

The effects of site on the costs of the cold water pipe are significant. Platform cost optimization should be affected by site since in some cases the CWP is 21 percent of the total platform cost.

3.1.2 Position-Keeping System

The two principal options are mooring and dynamic positioning. System characteristics and cost, derived in Section 2.3.4, are summarized in this section to illustrate system variation between sites and platforms. The three-point-spread mooring system is sized to hold the platform in the 100-year storm on only one leg of the moor. For the Key West site, this criterion is conservative as the moor would be deployed in the unidirectional current with each of two legs partially reacting the current drag. In addition, the anchor requirements are less stringent for a unidirectional current site. Therefore, the system costs for Key West may be reduced with these considerations.

In all cases analyzed, the dynamic positioning system costs exceeded the mooring system costs, excluding component replacement costs for both systems. Mooring system costs are summarized in Table 3-1 for each of six platform types and five sites for 100-MW(e) (net) plant output.

In all cases mooring system costs increase in the following order of sites.

Site	100-MW(e) Platform Variation (SM)
Hawaii	13 to 21
Puerto Rico	13 to 32
New Orleans	13 to 38
Brazil	34 to 46
Key West	62 to 30

Table 3-1

MOORING SYSTEM COST VARIATIONS WITH SITE ($ MILLIONS)
(EXCLUDING REPLACEMENT COSTS)

Platform	Net Output [MW(e)]	Hawaii	New Orleans	Brazil	Puerto Rico	Key West
Ship	100	17	28	44	20	62
	200	21	34	57	29	85
	500	35	63	109	54	184
Barge	100	18	33	45	27	67
	200	22	42	58	34	91
	500	39	77	121	63	199
Sphere	100	18	33	46	24	80
	200	25	44	70	38	117
	500	48	92	169	83	276
Semi-submersible	100	21	38	46	32	73
	200	26	49	69	39	101
	500	45	93	134	77	222
Submersible	100	13	18	34	18	62
	200	16	22	57	23	89
	500	28	42	120	47	206
Spar	100	16	23	45	22	74
	200	18	29	59	28	111
	500	36	59	156	62	267

The submersible platform mooring costs are the lowest in all sites, and that for the
sphere in Key West highest:

100-MW(e) Platform	Site Variation
Submersible	13 to 62
Spar	16 to 74
Ship	17 to 62
Barge	18 to 67
Sphere	18 to 80
Semisubmersible	21 to 73

Other site factors, such as fluctuation of current direction and frequency of storms,
affect system functional life and therefore replacement costs, which over a 40-year
plant life may exceed initial costs.

3.2 OPTIMUM PLANT EVALUATION FOR FIVE SITES

The evaluation process for the New Orleans site has been extended and applied to the
other potential OTEC sites. Examination of the qualitative (non-cost) factors (WANTS
2 to 11) shows that they are comparatively applicable for all the sites. The evaluation
scores for these items have been added to the comparative cost scores for the platforms
at the several sites to develop the total evaluation score. These are presented in
Table 3-2.

The detached spar configuration ranks first for all sites. This is chiefly a result of
the high qualitative score and the generally good cost scores. The internal spar ranks
second at all sites for the same reason even with a generally higher cost. The third-
ranked configuration is the circular barge nosing out the ship by virtue of the barge
being the lowest cost platform. The semisubmersible, Tuned Sphere, and the sub-
mersible rank lowest chiefly because of the low qualitative scores. High costs for the
semi and the Tuned Sphere further contribute to a low rank. The low cost of the sub-
mersible is not sufficient to overcome the lowest qualitative score.

Table 3-2

SUMMARY OF EVALUATION FOR COMMERCIAL PLANT [CONCRETE, 100 MW(e) (NET)]

		Ship	Circular Barge	Semi	Tuned Sphere	Sub	Spar (Int.)	Spar (Det.)
Subtotal of Qualitative Factors		173	166	142	145	134	201	222
New Orleans	Costs	90	100	80	80	100	80	90
	Total	263	266	222	225	234	281	312
	Rank	4	3	7	6	5	2	1
Puerto Rico	Costs	90	100	80	80	90	80	90
	Total	263	266	222	225	224	281	312
	Rank	4	3	7	5	6	2	1
Key West	Costs	90	100	80	80	90	80	90
	Total	263	266	222	225	224	281	312
	Rank	4	3	7	5	6	2	1
Keahole Point, Hawaii	Costs	90	100	80	80	90	70	80
	Total	263	266	222	225	224	271	302
	Rank	4	3	7	5	6	2	1
Brazil	Costs	90	100	80	80	90	80	90
	Total	263	266	222	225	224	281	312
	Rank	4	3	7	5	6	2	1

Section 4

IMPACT OF TECHNICAL ADVANCES

There are several potential technical advances in the areas of power generation and distribution which could have a salutary affect on platform cost of energy. In the following discussion only those advances which would have a significant impact on total cost are considered. Included in this section are proposed changes to power system components (e.g., heat exchangers).

4.1 HEAT EXCHANGER SELECTION

Estimates of vertical heat exchangers volume/MW(e) show a marked reduction relative to horizontal heat exchangers. For example, Gilbert Associates' data furnished to OTEC Commercial Plant contractors by the Government for their use in sizing studies show horizontal and vertical shell and tube heat exchangers to have volumes per megawatt of 3500 and 2770, respectively.

Even a greater potential improvement in heat exchanger power output may be derived through replacement of horizontal shell and tube by plate-fin heat exchangers leading to an improvement in volume per megawatt from 3500 to 670. The impact of platform costs for each of these possible power system modifications is described below.

4.1.1 Vertical Heat Exchangers

The improvement in platform dollars per kilowatt of net output power is presented in Table 4-1. Old $/KW refers to that attainable employing horizontal heat exchangers while New $/KW refers to the vertical heat exchanger equivalent. The latter data were obtained in the following manner.

The replacement of the horizontal heat exchanger by one of a higher power density has a number of side effects in addition to its main purpose of increasing total power output.

4-1

4-12

Table 4-1

PLANT $/MW(e) IMPROVEMENT THROUGH REPLACEMENT OF HORIZONTAL BY VERTICAL SHELL AND TUBE HEAT EXCHANGERS

P_O	P_N/P_O	P_N	Platform	Present Costs			Δ Costs			Plant Costs		$/KW(e)		% Decrease in $/KW(e)
				HX	CWP	SWP	HX	CWP	SWP	Old	New	Old	New	
100 MW(e)	1.064	106.4												
Concrete			$ 185M	$ 34.7M	$ 20.8M	$ 25.0M	$ 2.22M	$1.33M	$1.6M	$ 219.7M	$ 224.9M	2,197	2,114	3.3
Steel			$ 423M	$ 34.7M	$ 20.8M	$ 25.0M	$ 2.22M	$1.33M	$1.6M	$ 457.7M	$ 462.9M	4,577	4,351	4.9
200 MW(e)	1.064	212.6												
Concrete			$ 307M	$ 69.4M	$ 43.5M	$ 50.0M	$ 4.44M	$2.78M	$3.2M	$ 376.4M	$ 386.8M	1,882	1,818	3.4
Steel			$ 732M	$ 69.4M	$ 43.5M	$ 50.0M	$ 4.44M	$2.78M	$3.2M	$ 851.4M	$ 861.8M	4,257	4,050	4.9
500 MW(e)	1.064	532.0												
Concrete			$ 629M	$173.5M	$100.1M	$125.0M	$11.1M	$6.41M	$8.0M	$ 802.5M	$ 828.0M	1,605	1,556	3.1
Steel			$1,815M	$173.5M	$100.1M	$125.0M	$11.1M	$6.41M	$8.0M	$1,988.5M	$2,014.0M	3,977	3,786	4.8

Notes:
$8.675M per 25 MW(e) for horizontal shell and tube heat exchanger

$V_{P_N} = 2,770 \text{ ft}^3/\text{MW(e)}; V_{P_O} - 3,500 \text{ ft}^3/\text{MW(e)}, V_{P_O} = 1.264$

First of all, any increase in power output will require an essentially proportionate increase in CWP and seawater pump sizes. Note that such increases have been accounted for in Table 4-1.

A more subtle impact of increasing power density, is the corresponding increase in size of all the non-heat exchanger equipments in the power package-piping, demisters, turbo-generator, etc. In order to maintain a fixed power package volume, thereby eliminating necessity for redesigning the platform to accept the increased package size, an increase in the non-heat exchanger elements volume is necessary, thereby decreasing the total volume allotted to heat exchangers. Relationships which take this into account when computing the new power output are as follows:

$$\frac{V_{HX_N}}{V_{HX_O}} = \frac{\left[1 - .375 \left(\dfrac{V_{P_O}}{V_{P_N}} \right) \right]}{.625} \qquad (4\text{-}1a)$$

and

$$\frac{P_N}{P_O} = \frac{V_{HX_N}}{V_{HX_O}} \cdot \frac{V_{P_O}}{V_{P_N}} \qquad (4\text{-}1b)$$

where

V_{HX_O} = Volume of present HX (horizontal shell and tube)

V_{HX_N} = Volume of proposed HX

V_{P_O} = Volume/MW(e) for present HX (horizontal shell and tube)

V_{P_N} = Volume/MW(e) for proposed HX

P_O = Output of present Power System

P_N = Output of proposed Power System

.625 = Ratio of present HX to Power System Volume

4-3

Referring now to Table 4-1, the old and new $/KW were computed as follows. Replacing the horizontal (at 3,500 ft^3/MW(e)) with the vertical (at 2,770 ft^3/MW(e)) shell and tube heat exchangers, we substitute the ratio $V_{P_O}/V_{P_N} = 1.264$ into Equation 4-1, deriving a P_N/P_O of 1.064. P_N is presented for P_O, s of 100, 200, and 500 MW(e) which are the three plant sizes described in Section 2.4. For each plant size two platform costs are given — the lowest (cheapest platform in concrete) and highest (costliest platform in steel) — to provide a suitable range of potential cost improvements.

Also shown in the table are present heat exchanger, cold water pipe and seawater pump costs. The basic heat exchanger cost of $8,675K per 25 MW(e) power package has been scaled up proportionately for the 100, 200, and 500 MW(e) plants. Delta cost increases for these three elements have been obtained based on a linear extrapolation from present costs. The deltas are also shown in Table 4-1. The platform new costs are readily obtained by combining the deltas with the platform old costs. Finally, old and new $/KW and percentage improvement in $/KW are presented in the table and the latter are plotted in Fig. 4-1. It is apparent that the replacement of horizontal by vertical shell and tube exchangers at constant power package volume leads to only a minimal improvement in platform $/KW.

4.1.2 Plate-Fin Heat Exchangers

A similar analysis to that previously described was conducted assuming a replacement of horizontal shell and tube by plate-fin heat exchangers. Gilbert Associates data predicts the plate-fin heat exchanger to provide power at 250 ft^3/KW(e). It was necessary to resize this heat exchanger to provide a common base with the shell and tube. The result of this effort was a 670 ft^3/MW(e) power density for the plate-fin. The results of the $/KW and percentage improvement computation are presented in Table 4-2 and plotted in Fig. 4-1. A definite potential improvement is evident.

4.2 DEMISTERS

There is reason to believe that demister volumes called out in the Gilbert Associates Power System data package are conservative. It is likely that demisters ultimately

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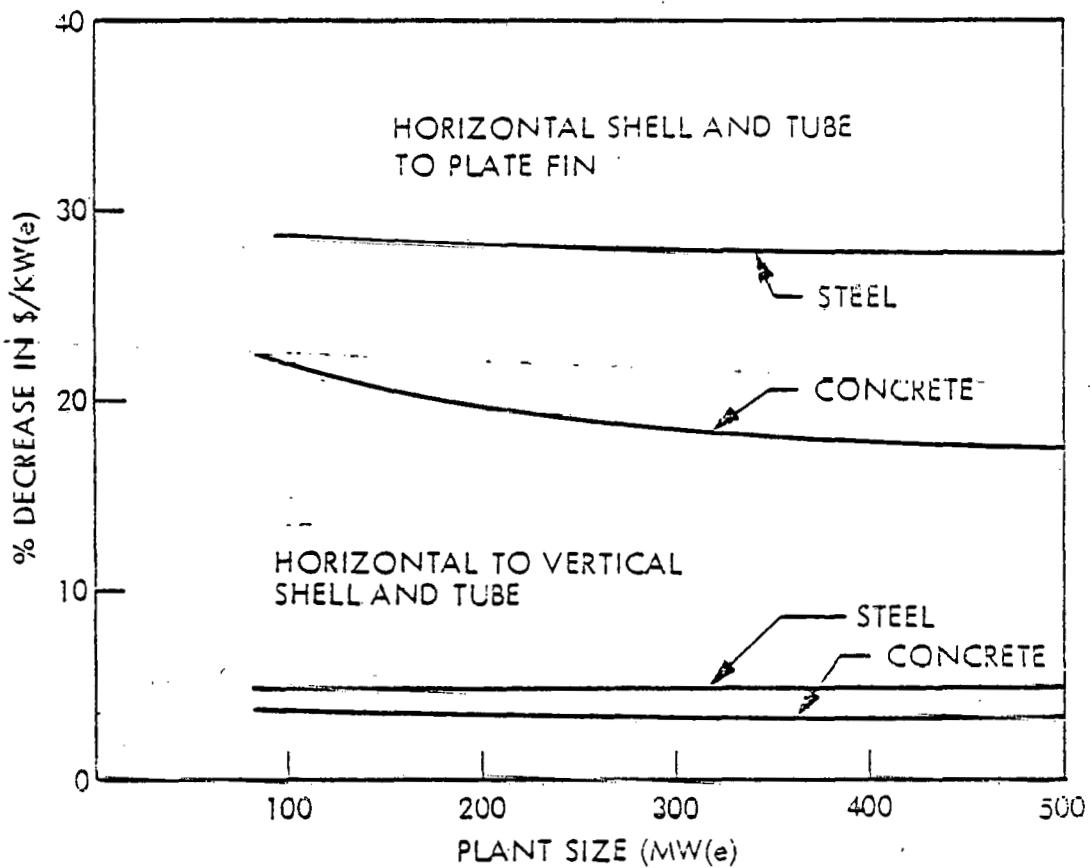
Fig. 4-1 Percent $/MW(e) Improvement Through Replacement of Horizontal Shell and Tube Heat Exchangers

employed in OTEC plants will be substantially smaller (predicted as low as 6.5 percent or lower of present values). If this is true, the extra volume could be devoted to increased power output through increase in size of heat exchangers and other Power System components. Employing the volume and cost data presented in Table 4-1 for 100-MW(e) steel and concrete platforms, Fig. 4-2 was prepared showing percent improvement in $/KW(e) as a function of reduction in demister volume. The percent increase in heat exchanger volume, from which the new net power output was determined, was based on the portion of the demister volume reduction which could be apportioned to the heat exchangers. The remainder of the reduction was apportioned to the remaining Power System components.

4-5

Table 4-2

PLANT $/MW(e) IMPROVEMENT THROUGH REPLACEMENT OF HORIZONTAL SHELL AND TUBE BY PLATE-FIN HEAT EXCHANGERS

P_O	P_N/P_O	P_N	Platform	Present Costs			Δ Costs			Plant Costs		$/KW(e)		% Decrease in $/KW(e)
				HX	CWP	SWP	HX	CWP	SWP	Old	New	Old	New	
100 MW(e)	1.534	153.4												
Concrete			$ 185M	$ 34.7M	$ 20.8M	$ 25.0M	$18.5M	$11.1M	$13.4M	$ 219.7M	$ 262.7M	2,195	1,713	22.0
Steel			$ 423M	$ 34.7M	$ 20.8M	$ 25.0M	$18.5M	$11.1M	$13.4M	$ 457.7M	$ 500.7M	4,577	3,264	28.7
200 MW(e)	1.534	306.8												
Concrete			$ 307M	$ 69.4M	$ 43.5M	$ 50.0M	$37.1M	$23.2M	$26.7M	$ 376.4M	$ 463.4M	1,882	1,510	19.8
Steel			$ 782M	$ 69.4M	$ 43.5M	$ 50.0M	$37.1M	$23.2M	$26.7M	$ 851.4M	$ 938.4M	4,257	3,059	28.1
500 MW(e)	1.534	767.0												
Concrete			$ 629M	$173.5M	$100.1M	$125.0M	$92.6M	$53.5M	$66.8M	$ 802.5M	$1,015.0M	1,605	1,323	17.6
Steel			$1,815M	$173.5M	$100.1M	$125.0M	$92.6M	$53.5M	$66.8M	$1,988.5M	$2,201.0M	3,977	2,870	27.8

Notes:
$8.675M per 25 MW(e) horizontal shell and tube heat exchanger

$V_{P_N} = 670 \, ft^3/MW(e); \quad V_{P_O} = 3,500 \, ft^3/MW(e) = V_{P_O}/V_{P_N} = 5.224$
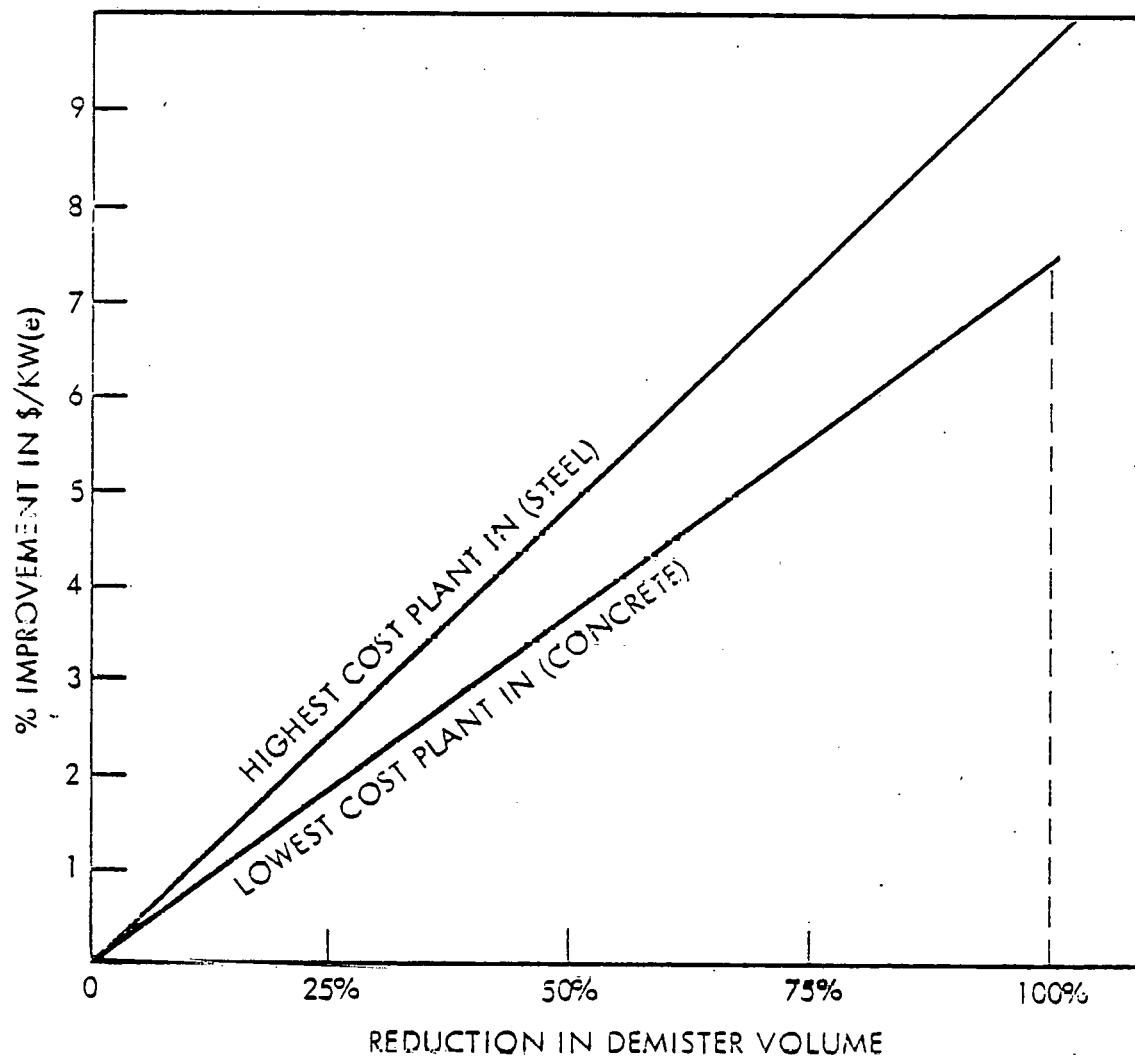
Fig. 4-2 Percent Improvement in $/KW(e) Through Reduction
in Demister Volume (for 100-MW(e) Plant)

Section 5
SUMMARY OF CONCLUSIONS

The following conclusions were derived in this study:

1. The requirements for the hull and structure are significantly affected by the requirements of the power system and the seawater system.

2. The requirements for the seawater system are significantly affected by the requirements of the hull-and-structure system and the power system.

3. The hull arrangements are primarily dictated by the requirements of the seawater system.

4. The size of the hull is primarily dictated by the size of the power system components, chiefly the heat exchangers and the turbine generators.

5. The optimum seawater ducting should be short and small in diameter.

6. The optimum cold water pipe is strongly affected by motions of the platform in high sea state conditions.

7. A concrete hull is estimated to be a significantly lower cost than a steel hull.

8. Four concrete platform configurations have essentially the same (±5%) initial capital cost. These are the circular barge, submersible, spar with detachable power modules, and ship, in order of increasing cost.

9. Three concrete configurations are significantly (10 to 20%) more costly than the four low-cost configurations. These are the spar with internal power module, tuned sphere, and semisubmersible, in order of increasing cost.

10. The larger the output of the power modules or of the OTEC plant, the lower is the cost of the platform per unit of output in the range of 50 to 500 MW(e) (net).

5-1

The following recommendations have been developed in this study:

1.   The most promising platform configurations for commercial OTEC plants are the spar with detachable power modules and the ship.

2.   The promising potential cost effectiveness of lightweight concrete for the hull should be verified.