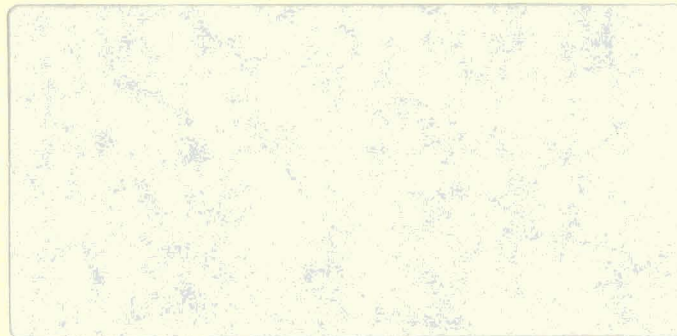


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OTEC PLATFORM CONFIGURATION AND  
INTEGRATION STUDY -  
FINAL REPORT

~~VOLUME 1~~

EXECUTIVE SUMMARY

April 1978 LMSC-D623756

Prepared for  
UNITED STATE 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

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## ABSTRACT

Conceptual designs of ship-type and spar-type platforms for Ocean Thermal Energy Conversion (OTEC) commercial plants are presented. Comparative evaluation of six candidate platform types is made. Design guidelines for sea water, cold water pipe and position control systems are developed. Costs are presented for plants with outputs of 400 MW<sub>e</sub> (Net) for operational sites of New Orleans, Hawaii, and Brazil.

## FOREWORD

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

Section 1  
INTRODUCTION AND SUMMARY

The OTEC commercial plant relies on the platform to provide all support functions for the OTEC power system. These functions include the structural support for the power system components, the supply of both warm and cold sea water, and the control of the position of the plant relative to the energy transfer system. The very large size of the components of the power system and sea water system dominates the arrangement and design of OTEC platform. The selection and conceptual design of the best types of platform for OTEC commercial plants is the objective of this study. This volume summarizes the significant requirements, design considerations and results of the study.

Energy derived by Ocean Thermal Energy Conversion (OTEC) depends on the passage of large quantities of sea water through heat exchangers which are optimized for the temperature differentials which occur between warm surface water in the tropics and the underlying cold water. Large capacity OTEC plants which would be economically attractive to commercial ventures, including power utilities, are the object of this study. These commercial OTEC plants would be comprised of power system components, the platform system, and a system for transfer of energy from the plant to the user. The power system extracts the energy from the sea water using heat exchangers to vaporize and condense a working fluid (usually ammonia), a low pressure turbine and generator, condensate pumps, and support systems. The transfer of the derived energy may be accomplished by a submerged cable for direct electrical transmission or by shipment of an energy intense product that would be processed at the plant. The OTEC platform which provides all support to the power system includes the hull and structure, the sea water system, the cold water pipe, the position control system, and support systems, Figure 1. Multiple OTEC plants may be closely arranged as an energy park.

This study is directed at developing the most satisfactory conceptual design of an OTEC commercial plant by integrating platform system and power system options. The power system options were defined for this study by the Department of Energy and were modified during the study as the result of information derived by con-

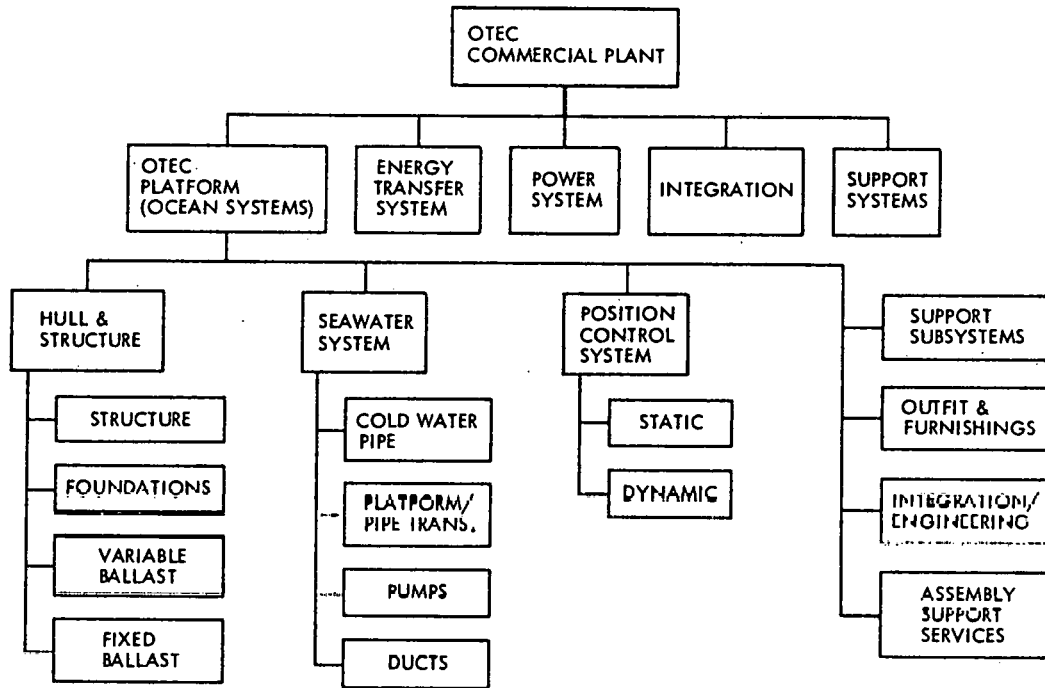


Figure 1. Work breakdown structure for OTEC commercial plant.

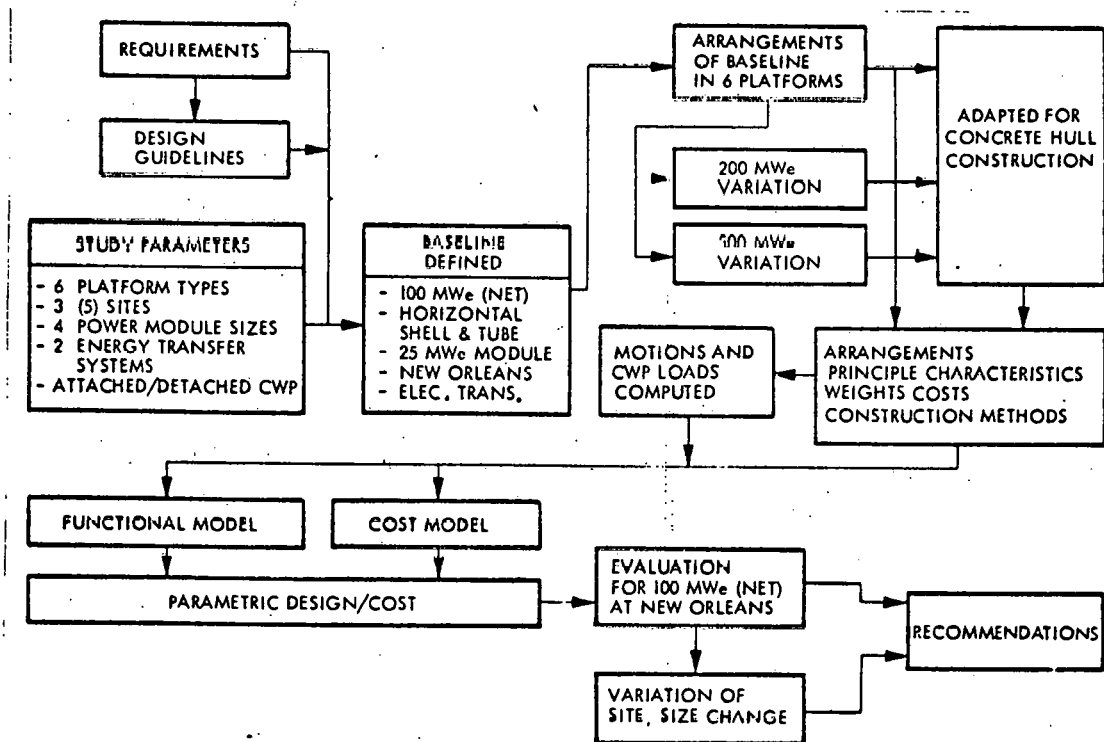


Figure 2. Approach to study of OTEC commercial plant.

current studies of power systems using shell and tube heat exchangers.

Platform systems were integrated into configurations representing the six conceptual types of platform for OTEC commercial plants. These configurations cover three depth ranges and include directional and omnidirectional types of platforms as shown below.

	<u>Directional</u>	<u>Omnidirectional</u>
<u>Surface</u>	SHIP	CIRCULAR BARGE
<u>Interface</u>	SEMISUBMERSIBLE	TUNED SPHERE
<u>Submerged</u>	SUBMERSIBLE	SPAR

The comparative assessment of these conceptual configurations was performed on the bases of baseline designs for each type of platform. These baseline designs were perturbed for application to other sites, power capacities, and materials for hull construction, as illustrated in Figure 2. An objective evaluation of these configurations, heavily weighted for economic considerations, resulted in the recommendation of two types of platforms for further refinement of conceptual designs. Under direction of the Department of Energy the conceptual designs of a ship and a detached spar platform were performed for 400 MWe (Net) commercial plants. Costs and construction schedules were developed for these two designs. Technology requirements to achieve these designs were determined. A plan for demonstration of commercial plants was prepared.

The significant results of this study are the following.

1. The cost to construct hulls for OTEC platforms to contain internally-installed power system components are estimated to be significantly less (about 32%) in concrete than in steel.
2. Sea water ducts inside a platform hull are very expensive. Minimum lengths and optimized diameters of sea water ducts are recommended for economic and weight considerations. Immersed ducts are also recommended to reduce cost and weight.
3. The sea water pumps are a major cost of the OTEC platform. Trade studies for arrangements, reliability, multiple units, and cost are inconclusive at

this conceptual design stage of the platform and power systems.

4. Flexibility is required in cold water pipes to minimize the impact of platform motions on the wall thickness, weight and cost of the pipe. Replacement and deployment costs may be significant considerations in pipe optimization.
5. Conceptual designs for OTEC platforms for externally mounted power system components for 400 MWe (Net) have resulted in cost estimates of 690 \$/KW for the ship-type platform and 801 \$/KW for the detachable spar for the New Orleans site.

This volume (Vol. 0) presents the executive summary of this study. Volume 1 presents the results of the systems integration and assessment of the six conceptual platform configurations. Volume 2 presents the detailed results of the conceptual design of the ship-type platform and the detachable-spar platform. Volume 3 presents recommendations for demonstration of the commercial OTEC plant.

Section 2  
REQUIREMENTS FOR OTEC PLATFORM

The requirements for the OTEC platform 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. (Later relaxed to 25 percent.)
5. The platform must survive a 100-year storm (as described in Table 1).
6. The platform must be constructable and operable under prevailing codes and rules.
7. The platform must accommodate a power system and seawater systems.
8. The platform must allow the power system to operate efficiently at all times that the thermal resources exist.

Power system components for the comparison of platform types were defined for modules of complete power systems each having an output capacity of 5, 8, 12-1/2, and 25 MWe. The power system uses ammonia for a working fluid. Arrangements of these components indicated that the 25 MWe capacity components were more efficient in the use of volume and floor space than were the smaller capacity modules. In addition, the 25 MWe components as defined were the least costly of the power system modules. The potential for greater efficiency of packing the smaller units into the six hull configurations did not seem to offset other design considerations (primarily manifolding the seawater system to serve the additional number of heat exchangers). The 25 MWe module was used as the baseline power system in the assessment of the platform types.

The power system defined for the conceptual design was based on power modules of 25 and 50 MWe (Net) with either horizontal or vertical heat exchangers.

Table 1

OTEC Site Environmental Characteristics (100 year storm)

<u>PARAMETER</u>	<u>BRAZIL</u>	<u>HAWAII</u>	<u>PUERTO RICO</u>	<u>KEY WEST</u>	<u>NEW ORLEANS</u>
MAX WIND (Kts)	61	66	93	114	100
$H_{1/3}$ (ft)	29	36	44	46	58
CURRENT (Kts)	3.2	2.2	2.8	6.4	2.5
DEPTH (ft)	18,000	3150	4000	4850	3950

### Section 3

#### ASSESSMENT OF PLATFORM TYPES

Arrangement of the components of the power systems in conjunction with the components of the seawater system within the six hull configurations was the primary design task. The complexity of these arrangements is typified by the small (12-18%) packing ratios (volume of power system components/displacement of platform) which were able to be obtained with the power systems inside these hulls. The large flow of water required for operation of the OTEC power system resulted in the seawater system occupying the major volume in the platforms. The results of preliminary trade studies for the seawater systems are as follows.

The seawater pumps for OTEC application are pressing the state-of-the-art for flow rate and the resultant large physical size of the pumps. Limited available information, Ref. 1, indicated that larger pumps are more cost effective. Hence, a single pump per duct would appear to be the best cost choice. Considerations of reduced output of the power system in the event of pump failure indicate that three or four pumps per duct would be preferred even though they are more costly. These arguments do not consider the cost impact on the platform for the larger volume and floor space required for the single large pump as compared with the shorter length and smaller packaged volume for multiple pumps. The cost to provide volume on the platform is estimated in this trade study at \$650 per cubic metre (\$18.50/ft<sup>3</sup>). The total cost of multiple seawater pumps including the value of the volume occupied on the platform leads to essentially identical costs for either the single or multiple pumps serving the same 25 MWe output, Fig. 3. Costs of seawater pumps in this case are not the deciding factor when platform costs are included in the comparison. Freedom in component arrangements and power system availability then become the factors which affect the design choice of one or multiple pumps per duct.

The large flow rate requirements (156 ft<sup>3</sup>/sec per megawatt/heat exchanger) for the OTEC power system require large seawater ducts. The size of these ducts affect the arrangement of components, the minimum radius of turns of

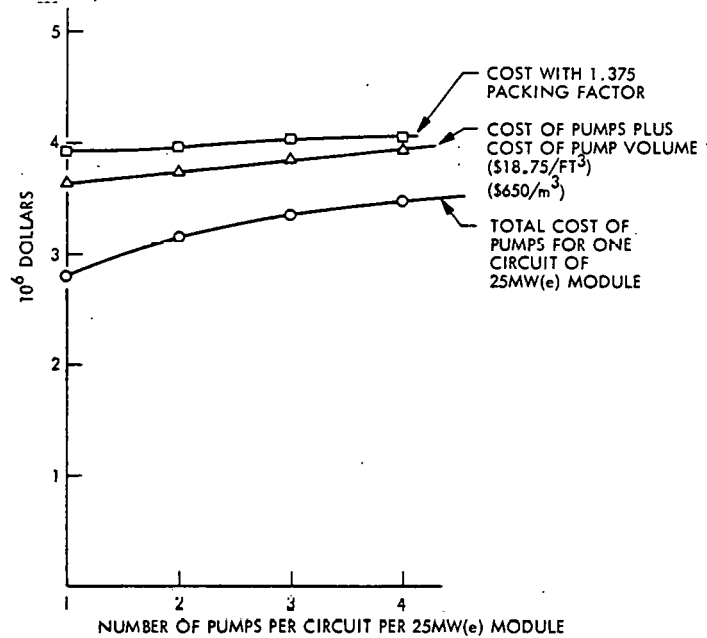


Figure 3 Total cost of multiple seawater pumps for one circuit of a 25 MW<sub>e</sub> (Net) power module.

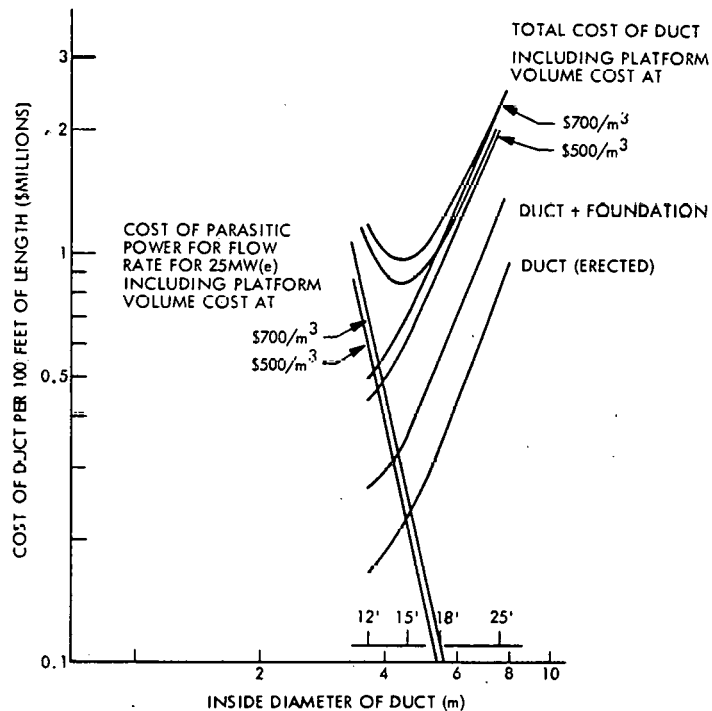


Figure 4 Total cost of seawater ducts per 100 ft of duct.

the duct, the weight of water carried in the duct, the volume occupied in the hull, and the weight of the pipe and the foundation to support the pipe in the hull. A smaller pipe would reduce all of these factors at the expense of increased requirements for pumping power. The optimum duct diameter is about 4.5 metres (15 ft) for a 25 MWe module, Fig. 4, when these factors are considered. This results in a water velocity of about 5 m/s (15 fps). This high flow can cause significant losses in turns, nozzles, and diffusers and must be carefully considered in detail design so as to avoid excessive flow losses. More generous design conditions were used in the comparison of the six hulls configurations to assure adequately conservative arrangements.

The cold water pipe is considered to be the key technical system on the platform. This is the result of the large diameter 17M (54 ft) and length 1000m (3281 ft) of the pipe for a 100 MWe platform when all of the cold water is taken in one pipe. The platform motions in a seaway cause large loadings to be imposed on the pipe. Studies, Ref. 2, 3, have indicated that a moderately flexible (not rigid, not pinned) attachment should occur between the pipe and the OTEC platform to best balance the bending moment distribution over the length of the pipe. These results indicate that there is only a small influence of the pipe loads on the motions of the platform for reasonable values of attachment stiffness. Motions computed for the six baseline configurations developed in this study are shown in Fig. 5 for the 100 MWe plant in seas with a significant wave height of 58 ft. The surface platforms have large motions and the submerged platforms have small motions. The tabulated surge motion seems to correlate best with the maximum bending moments in the cold water pipe. Early analysis showed that flexibility in the pipe is required to keep the loads to reasonable design values. To this end, pipe designs were considered for aluminum, glass reinforced plastic (GRP) and concrete with flexible joints ( $E = 0.3 \times 10^6$  psi). The estimated wall thickness varies widely depending upon the design environment, such as significant wave height, Fig. 6. The budding limit, Ref. 1, controls the design thickness for low sea conditions. At high seas and varying with platform motions the estimated wall thickness becomes large, up to 5 ft. for a spar platform in a significant



wave height of 58 ft, which is the 100 year storm condition for the New Orleans site.

The depth at which the pipe is attached to the platform has a significant effect on the maximum dynamic bending moment in the pipe. A large (2.5 to 1) reduction in required pipe thickness occurred with high attachment (near the CG) for the spar as compared to a deep attachment (below the base of the spar). Computations for a spar platform show that in a seaway the maximum dynamic bending moment along the pipe is a monotonically decreasing function of the elevation of the pipe attachment to the platform, Fig. 7. Other platforms appear to have optimum attachment elevations which vary with design sea conditions. More detailed assessment of the ideal attachment location and type of attachment stiffness is required for more advanced designs of the cold water pipe. Further conceptual design considerations for the pipe are presented in Section 4.

A concrete pipe with flexible joints was selected for the comparison of platform configurations with wall thickness dependent upon the extreme significant wave height for each site and the bending moments induced by the platform motions. The cost of the pipe varied by a factor of 2 among the sites and a factor of 2.4 among the platforms. The pipe cost for the ship at New Orleans was estimated to cost 79% as much as the construction cost of the ship hull and structure. Significant development effort is needed to reduce the probable cost of the cold water pipe system.

The position control system provides close (25 percent watch circle) control of platforms in all environmental conditions. Because of the need to locate OTEC plants in water which has an adequate supply of cold water, the position control system is also a costly system. The real costs for a moored system (anchors and multiple lines) and a dynamic positioning system are presented in Fig. 8. These costs include replacement costs for the mooring lines and power costs for the thrusters. They do not include the costs for additional

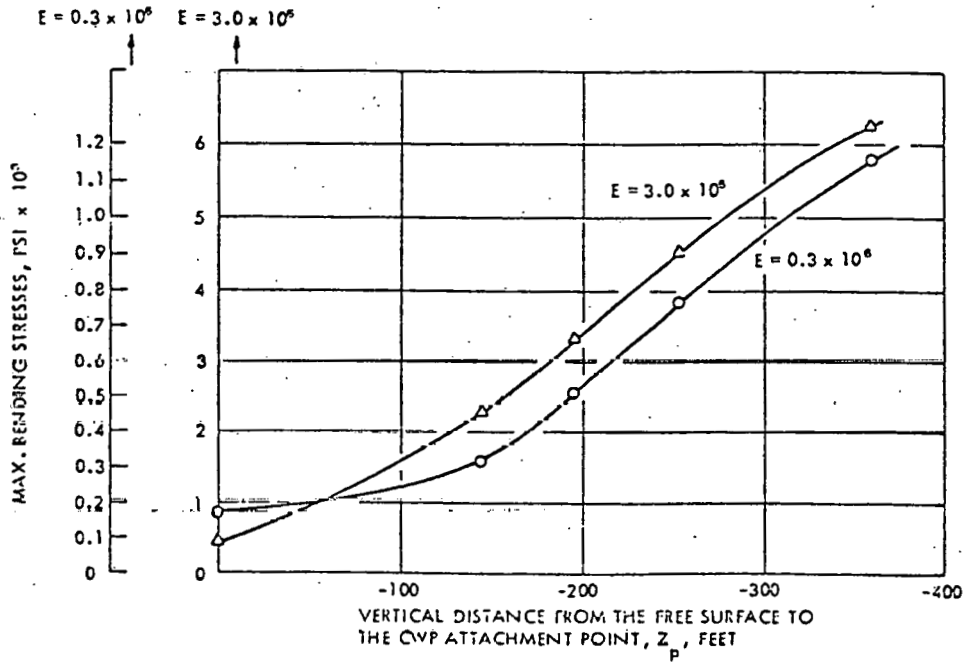


Figure 7 Maximum bending stress in cold water pipe in a seaway ( $H_{s1/3} = 45.8$  ft) as a function of depth of attachment to the spar.

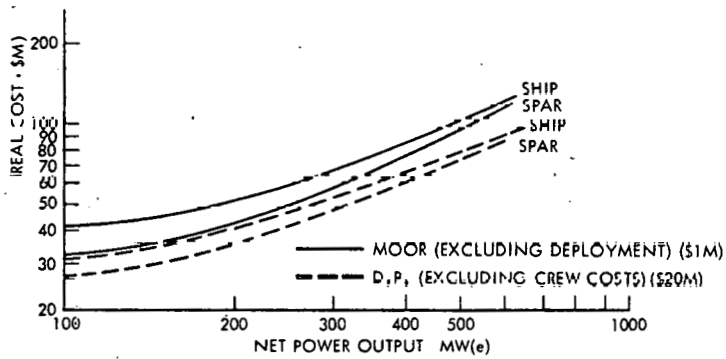


Figure 8 Real cost of position keeping system, New Orleans

personnel that may be required to operate the dynamic positioning system for the planned 40 year life of the plant. Inclusion of personnel costs (estimated at \$20 million) would favor the moored system for smaller platforms (up to 400 MWe). Since these costs are quite close, considering the environmental approximations used in the analysis, a mooring system was used for this comparative evaluation of platforms. However, both types of systems should be retained for consideration when more refined analyses with adequate site data are available.

These platform systems were incorporated into the platform arrangements with the power system components to develop the baseline designs for the 100 MWe (net) commercial plant at the New Orleans site. The comparative size, shape and features of these designs are illustrated in Fig. 9 for internally-mounted power components and in Table 2 which also includes the principal characteristics of a spar with detachable power modules. This later configuration is very similar to that reported in a previous study, Ref. 4.

It is evident from the operating drafts for these platforms that they cannot be constructed in existing U.S. ship yards or in close-in coastal water. The construction of these platforms in steel hulls was predicated upon a three stage construction method which moved into deeper, water at higher costs as the hull draft is increased. A similar approach for concrete construction has been offered. Costs have been developed for both steel and concrete hulls. The system cost percentages are presented in Table 3 for a spar platform with detachable modules. The steel hull and structure is estimated to be 2.2 times as costly as the concrete hull and structure. The overall platform costs are 1.46 times as costly for the steel as for concrete.

The total costs for the six platform types are illustrated in Fig. 10 for concrete hull structures. The detached module spar is also included in this comparison. Four platforms constructed in concrete were estimated to cost within 9 percent of each other. These are the circular barge, the submarine, the detached spar, the ship. The other three configurations range from 18 to 21% more costly than the circular barge and at least 9 percent more costly

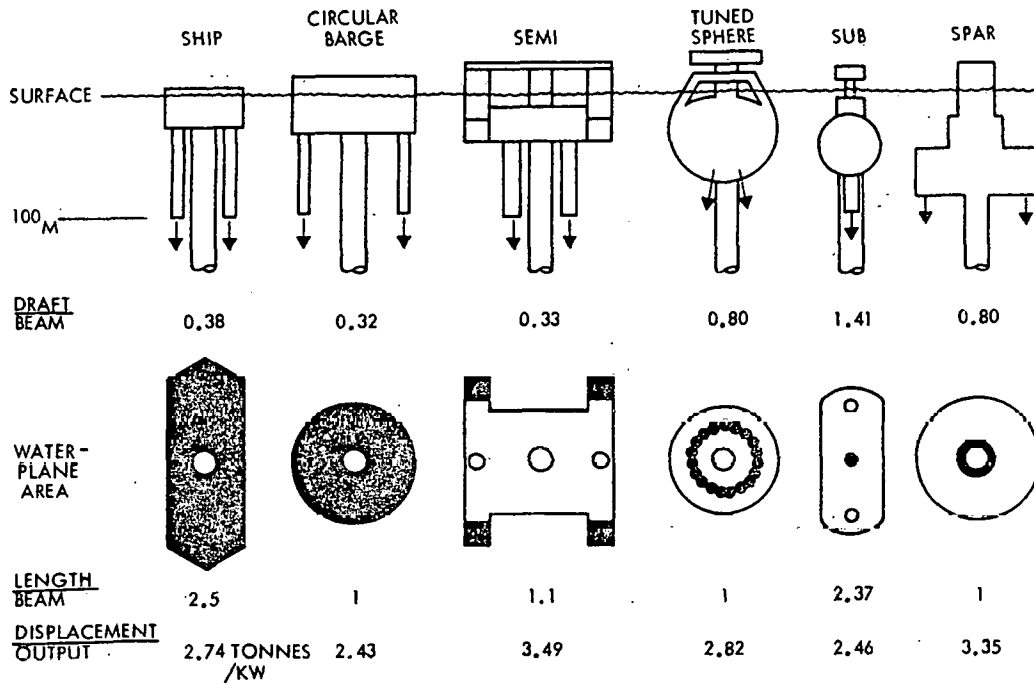


Figure 9. Platform configurations for 100 MWe (Net) OTEC commercial plant with internally mounted power system.

Table 2  
Summary of Principal Characteristics - 100 MWe (Net) OTEC Commercial Plant

	SHIP	CIRCULAR BARGE	SEMI	TUNED SPHERE	SUB	SPAR (INT)	SPAR (DET)
LENGTH (metres)	171	98	136	91	124	100	98
BEAM (metres)	72	98	124	91	56	100	98
HEIGHT (metres)	37	43	64	102	90	115	140
DRAFT (metres)	27	24	44	73	72	80	115
DISPLACEMENT (thousand metric tons)	274	284	350	129	254	234	118

Table 3  
 Percentage of Capital Cost by Subsystem - 100 MWe (Net),  
 Spar With Detachable Power Modules.

SUBSYSTEM	HULL MATERIAL	
	STEEL	CONCRETE
HULL & STRUCTURE	52%	36%
COLD WATER PIPE	6%	9%
SEAWATER PUMPS & DUCTING	9%	13%
POSITION CONTROL SYSTEMS	7%	10%
AUXILIARY SYSTEMS	11%	10%
OUTFIT & FURNISHINGS	6%	8%
DEPLOYMENT & CWP ASSEMBLY/INSTALLATION	9%	14%
TOTAL	100%	100%
TOTAL COST TOTAL COST CONCRETE	1.46	1.00

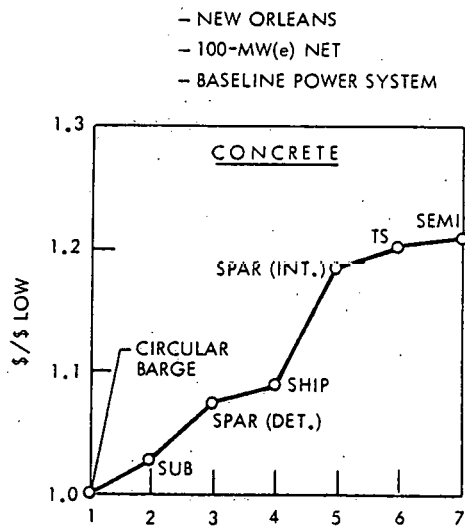


Figure 10. Comparative costs of seven OTEC platform configurations.

than the ship. These were the internal spar, the tuned sphere, and the semi-submersible which was most costly in concrete. The closeness of these results (less than  $\pm 5\%$ ) for the first four configurations indicates that they should continue to be considered equal on a cost comparison basis. An evaluation of these seven platform configurations was performed based upon nine qualitative criteria and one (low cost) quantitative criteria. This process also included an assessment of risks of completing successfully the development of the planned commercial plant for each platform type. Fig. 11 presents the tabulation of these evaluation and risk assessment scores for the 100 MWe (Net) commercial plant at New Orleans when constructed of concrete. The development risk factors have been presented as negative scores from 0 to -100 indicating increasing (toward -100) risk which should be weighted against the positive scores. In all cases (50 to 500 MWe (net)) the analysis indicates that the larger the power module capacity and the larger the platform capacity the lower is the cost of the platform per unit output of energy.

The two spar types rank high on total score followed closely by the circular barge and the ship.

On the basis of these results it is recommended that further development efforts should consider the spar type platform both with detachable and internal power systems especially in areas of high seas and where electrical power transmission is planned. The spar has outstanding motion characteristics in a seaway, is low cost, has an optimum mooring system which is independent of storm direction, and imposes the least stringent design requirements on the cold water pipe. A ship-type platform is recommended for consideration along with the spars at sites where grazing is planned, or at which electrical transmission is not planned. The ship has low powering requirements for grazing, mode, mode, has moderate motions in a head sea condition, and is low cost.

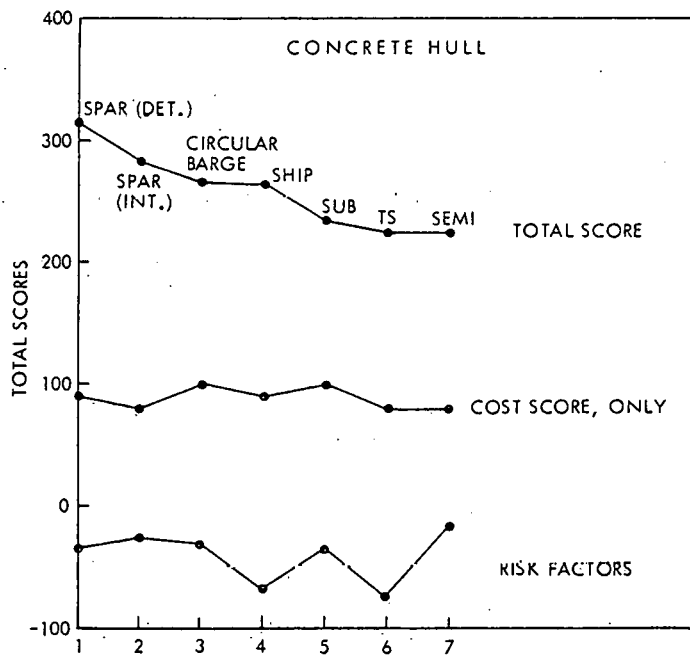


Figure 11. Evaluation of best OTEC platform for 100 MWe output at New Orleans site.

Section 4  
CONCEPTUAL DESIGN OF COLD WATER PIPE

The previous analysis for cold water pipes of 54 feet inside diameter for 100 MW e showed that of the materials investigated prestressed concrete with flexibly joined sections was the lowest cost concept. However, the resultant payload requirement on the platform, particularly on the non-floating concepts, was reflected in a high cost penalty. This conceptual design considers alternatives to the materials previously investigated as well as approaches to reducing the weight of concrete pipe.

Pipe characteristics investigated conceptually were diameter, length, thickness, material, joints, deployment, and platform attachment. The significant results of these analyses are the following.

1. The optimum inside diameter of pipe for a 400 MW(e) commercial plant is in the range of 21 to 24 meters (70 to 80 ft) for concrete, Fig. 12.
2. Optimum pipe length is 808 meters (2650 ft) for a concrete pipe on the spar in New Orleans for an inlet depth of 900 meters (2950 ft), Fig. 13.
3. Pipe wall thickness, strongly dependent on material, lies in the range of 0.5 cm (1/4 inch) for rubber-nylon to 0.3 meters (1 foot) or more for jointed concrete.
4. Among the rigid materials investigated (concrete, GRP, aluminum), the reinforced concrete pipe with flexible joints is the lowest cost pipe material, Fig. 14.
5. The rubber-nylon concept is an attractive alternative to concrete from the standpoint of low weight and cost if the material life in seawater is equal to that of concrete. The high cost for deployment of the

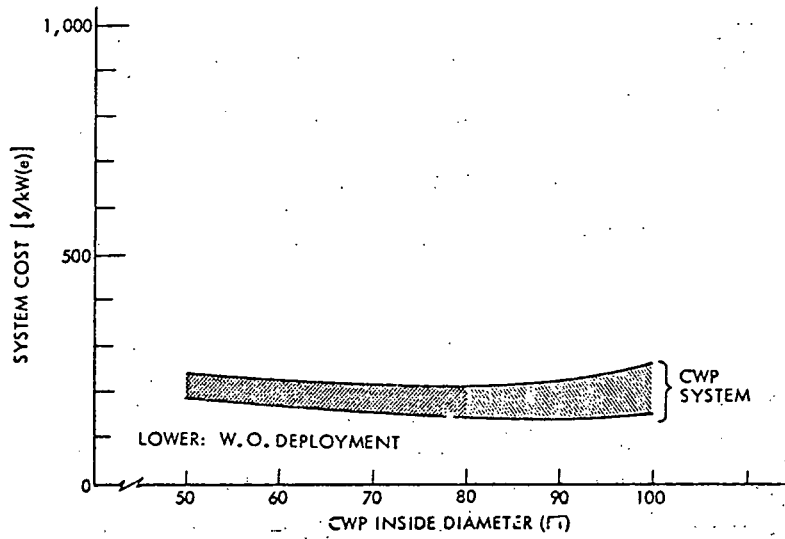


Figure 12 Cost optimization of cold water pipe diameter for 400 M<sub>e</sub> (Net) commercial plant at New Orleans.

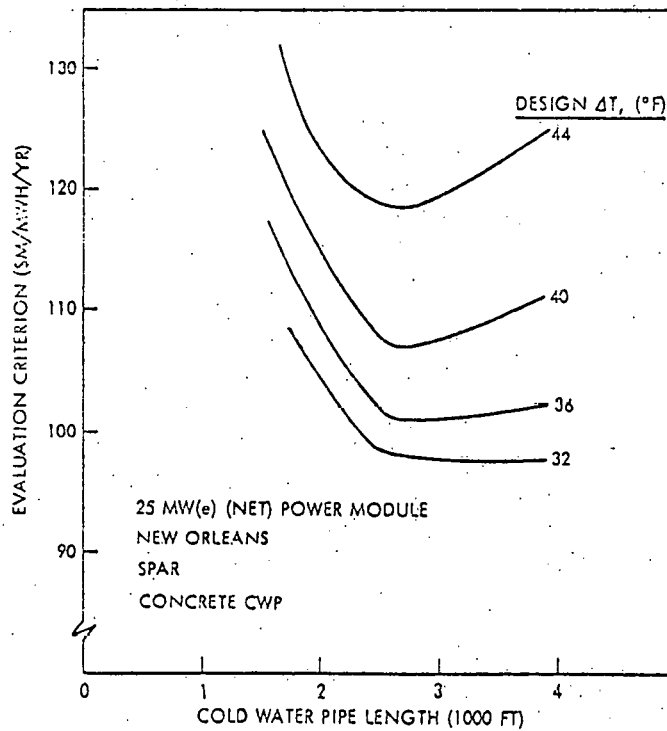


Figure 13 Optimization of cold water pipe length.

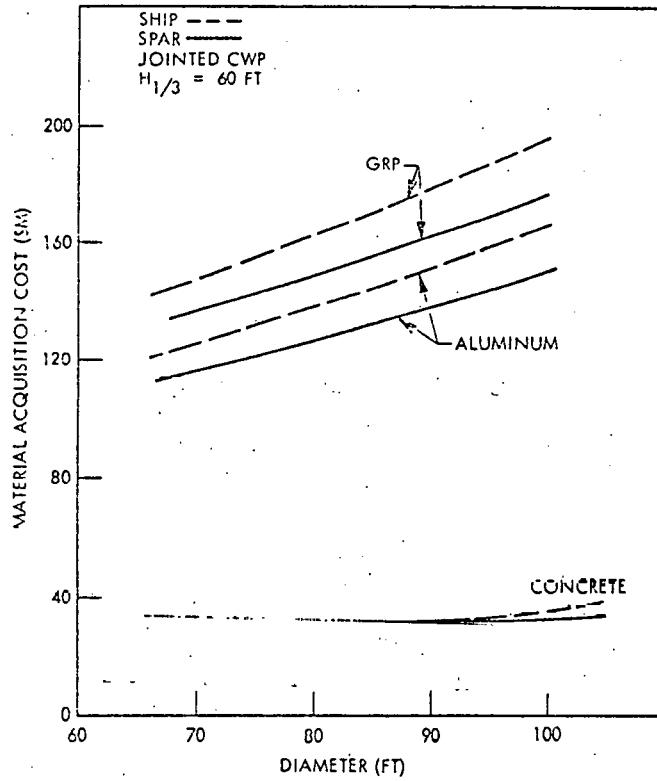


Figure 14. Construction costs of cold water pipe.

Table 4

Construction and Deployment Costs for Cold Water Pipe. (\$ M)

(400 MWE PLANT AT NEW ORLEANS)

PLATFORM TYPE CWP MATERIAL	SHIP		SPAR	
	SOFT	CONCRETE	SOFT	CONCRETE
CONSTRUCTION	31.9	27.9	29.6	25.0
DEPLOYMENT	5.1	21.1	4.5	19.0*
TOTAL	37.0	49.0	34.1	44.0

\*DOES NOT INCLUDE ADDITIONAL COST OF OFFSHORE  
 CONSTRUCTION OF TOP OF SPAR PLATFORM

heavy concrete pipe overshadows the lower construction cost, Table 4. If not, then the costs to deploy a replacement rubber-nylon pipe(s) in the forty years of plant operation would make this concept non-cost competitive with concrete.

6. Flexible joints have been devised for rigid pipe sections which provide for ease of deployment as well as fail-safe continuous operation in storms. The latter by limiting pipe bending stresses through pre-determined levels of rotational fixity. Connections for pipe sections of other materials not requiring this latter characteristic would be less costly.
7. Deployment of the pipe for any of the rigid concepts consists of sequentially lowering, by a jacking system, each pipe section through a temporary opening and cofferdam. This approach applied to the spar would be carried out in deep water on the base structure prior to slip forming of the core, the latter fitted with temporary buoyancy tanks to support the CWP.
8. Deployment of the soft, rubber-nylon pipe would consist of lowering the pipe and attaching to the platform from below either the ship or spar.
9. Attachment to the platform in the case of the rigid pipe concept requires a bearing to minimize platform-induced pipe bending stress in a hurricane. This approach may not be required for the rubber-nylon pipe where the pipe wall is assumed to stretch under bending applied at the pipe-platform interface, thereby relieving tensile stress.

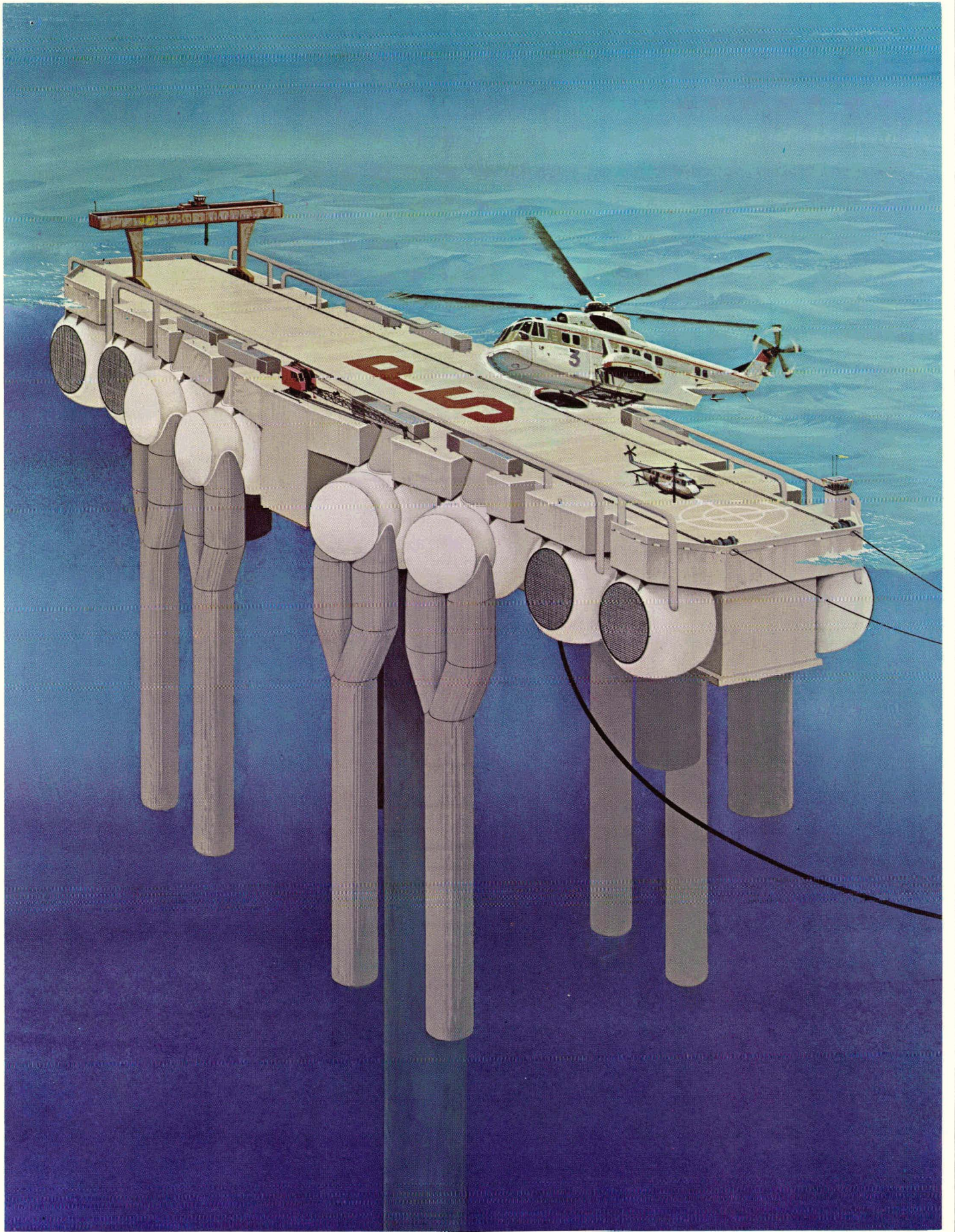
## Section 5

### DESCRIPTION OF CONCEPTUAL DESIGN OF SHIP PLATFORM

The conceptual design for a ship-type platform for a 400 MW e (Net) OTEC commercial plant is a major departure from conventional ship design. The unusual payload requirements of the OTEC power system and seawater flow systems have been efficiently integrated with the ship structural requirements to create a unique platform concept for the commercial plant.

Initial concepts for the ship platform centered on mounting the 50 MW e (Net) power system components interior to the concrete hull structure in arrangements that sought to optimize the seawater ducting. The cost estimates for these new concepts supported the platform costs previously developed for comparison of types of platforms.

Significant reductions in platform costs obviously require non-traditional approaches. A major portion of the ship hull structure had been devoted to providing displacement (as is traditional) to contain the power system components. Noting that many power system components themselves were pressure vessels and some displaced large volumes of water, it was decided to apply these components to provide buoyancy for the platform. The heat exchangers were fully immersed in seawater by removing the outer hull of the ship. Immersion of the heat exchangers also has been shown to reduce the cost of the hull. The seawater ducts within the hull were redesigned to thinner sections as a result of the reduced pressure differential across the wall. This new strong-back-type structural arrangement of the ship then required special consideration for construction and float-out limitations. Lightweight concrete was used to further reduce the size and weight of hull structure. Another feature of this arrangement is that it allows the large heat exchangers to be floated into position from the open sides of the structure, eliminating the need for cranes to lift the entire heat exchanger.



OTEC PLANT SHIP

LOCKHEED MISSILES & SPACE COMPANY

# LOCKHEED OCEAN THERMAL ENERGY CONVERSION (OTEC) PLANT SHIP

## WHAT IS OTEC?

OTEC means Ocean Thermal Energy Conversion. OTEC is a means for extracting solar energy from the oceans by using the difference in temperature between the warm tropical surface waters and the cold deep waters. The temperature difference is used in a power cycle very similar in principle to the conventional power plants that use the heat of burning coal or gas.

## HOW DOES OTEC WORK?

The working fluid in OTEC such as ammonia is vaporized in an evaporator heated by the warm surface water. The vapor is expanded through a turbine which drives a generator to make electricity. The vapor is then restored to liquid form in the condenser, cooled by the cold deep-sea water. The condensed liquid is returned to the evaporator to repeat the closed cycle process.

## WHAT IS THE OTEC PLANT SHIP?

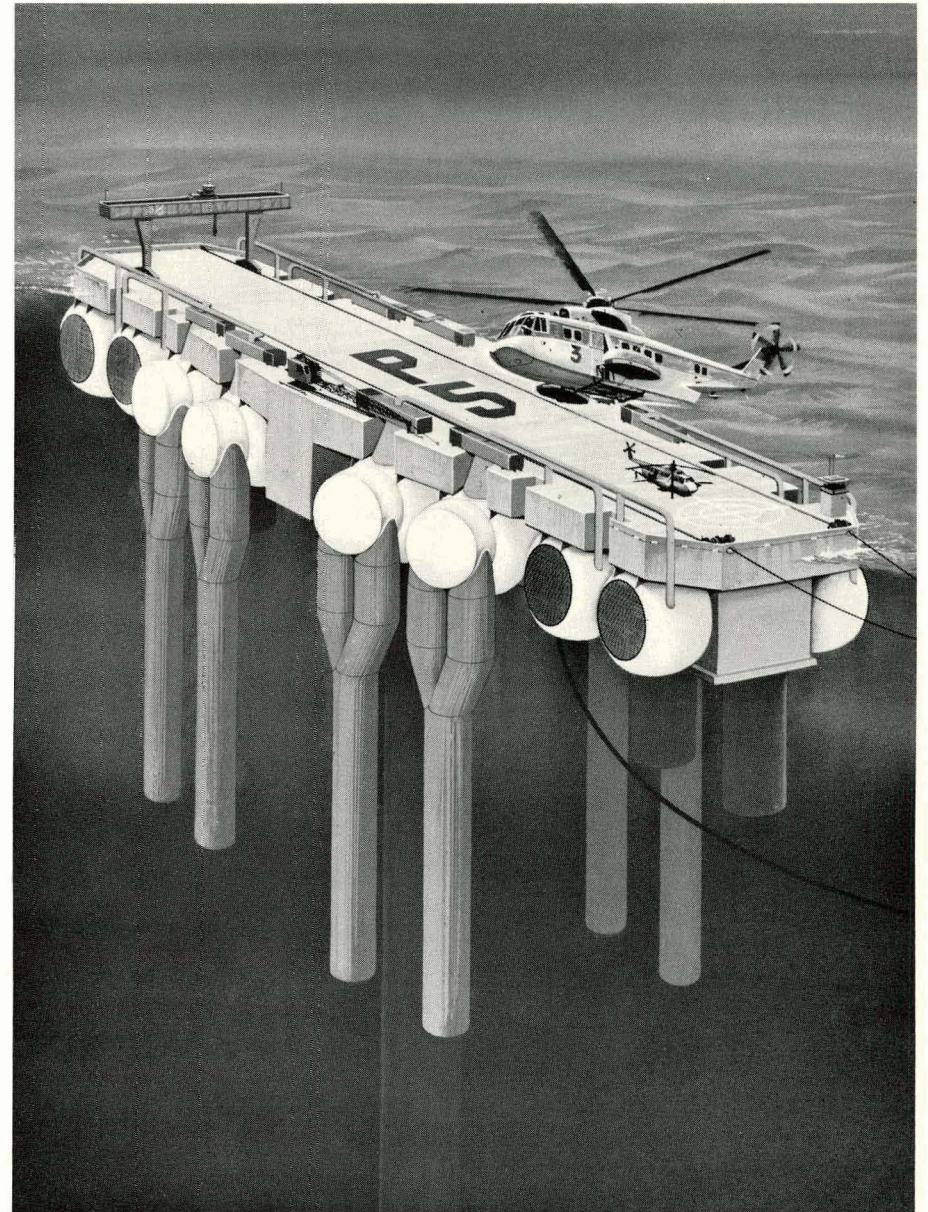
The OTEC Plant Ship is a cost effective arrangement of the subsystems of an OTEC plant that can cruise the high seas, following the most favorable ocean temperatures. The heat exchangers which are immersed in the sea water to provide buoyancy are arranged around the ship adjacent to the warm and cold water ducts. These heat exchangers can be detached from the hull and floated to a base for servicing. The ship-like shape of the platform simplifies the cold water pipe and the position keeping system.

## WHAT CAN THE OTEC PLANT SHIP DO FOR US?

The electricity generated by an OTEC Plant Ship can be used to produce energy intensive products such as hydrogen and ammonia, which can then be transhipped to the marketplace by other vessels. And it can do so safely and without harming the ocean environment. Furthermore, the solar energy it uses is replenished constantly.

A single 400 megawatt plant ship producing ammonia can save 38 million cubic feet per day of natural gas.

The U. S. Government supports OTEC design and development through the Department of Energy (DOE).



The OTEC Ship Platform consists of a central concrete hull, external heat exchangers attached to both sides of the hull, cold water intake and warm water discharge pipes attached to the bottom, warm and cold seawater pumps in the discharge piping, and support system equipment on the Main and Second Decks, Fig. 15. The ship has the principal characteristics shown in Table 5:

The central hull is "T"-shaped in cross-section and wall-sided throughout. The arrangement was developed to minimize weight and cost, and yet provide sufficient buoyancy, strength, internal volume, and deck area for all required OTEC equipment under the anticipated environmental conditions. Permanent accommodations have not been provided for the moored configuration. It is anticipated that all operating and maintenance personnel will be housed ashore or in an accommodations vessel centrally moored in the energy park. The hull is designed for construction in a graving dock with a 46 foot draft at float-out.

The buoyant heat exchangers will be readily detachable for repair or major maintenance ashore. Attachment to the hull will be made on the underside of the wing walls and by means of mating flanges in way of the openings in the side walls of the hull.

Four evaporators will be located at each end of the vessel, (2 port, 2 starboard). The evaporators will draw directly from the surrounding warm water through screens and discharge into warm water plenums and down through discharge pipes. The eight condensers will take water from a common cold water plenum which is filled by the cold water intake pipe and then discharge outboard and down through the discharge pipes to 150 m depth.

The pumps for warm and cold water are located on the discharge side of the heat exchangers with two pumps serving each. The pump/pipe unit for each heat exchanger module is designed to be slightly buoyant and detachable for transport to shore facilities for major repair and maintenance. The

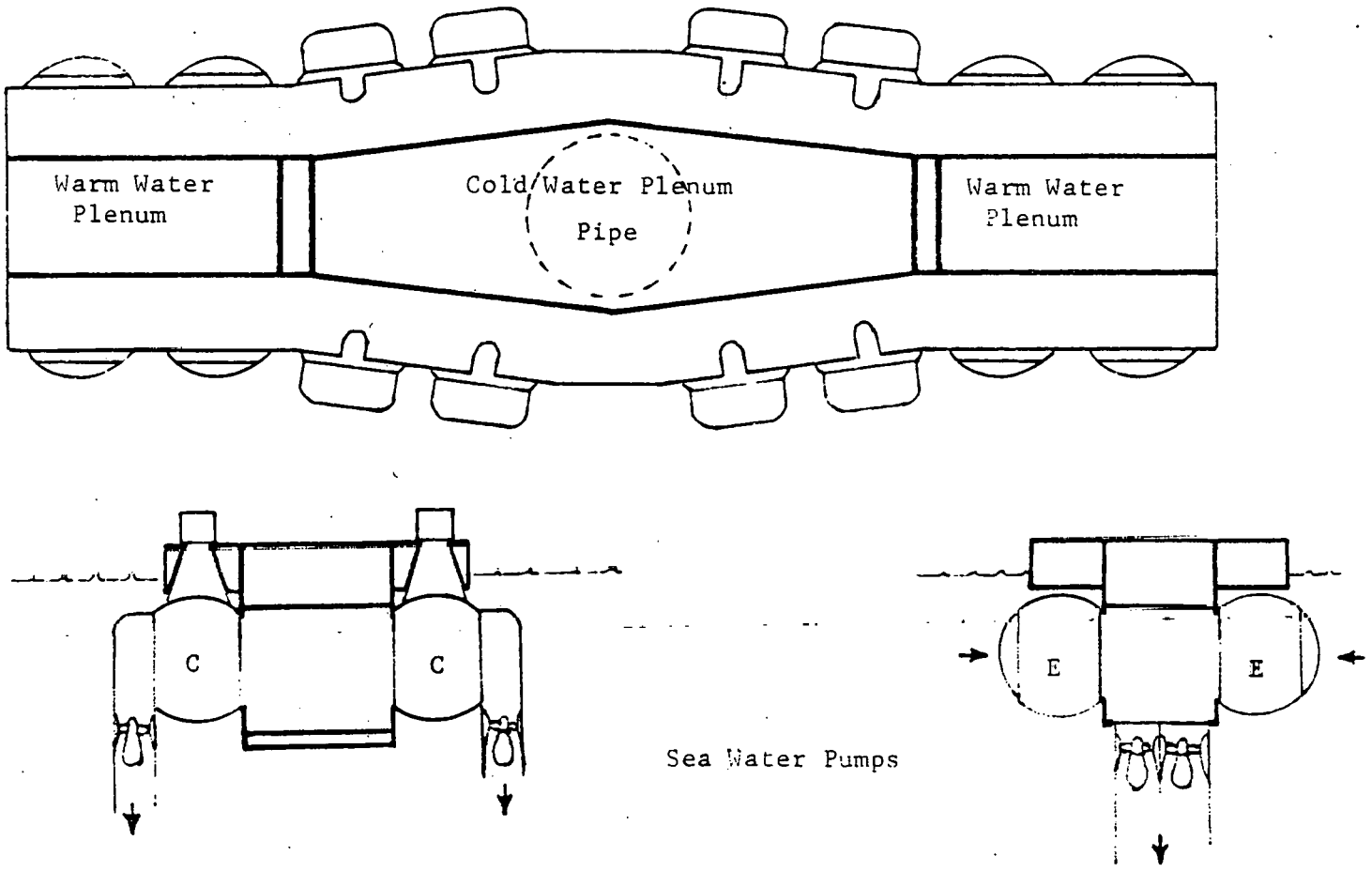


Fig. 15 Configuration of ship-type OTEC commercial plant.

Table 5  
Principal Characteristics of Ship-Type OTEC Commercial Plant,  
400 MW<sub>e</sub> Net, New Orleans

Length Overall	210 m	689 ft
Maximum Beam on Waterline	58 m	190 ft
Maximum Beam Overall	73 m	240 ft
Depth to Main Deck	34 m	112 ft
Operating Draft	28 m	92 ft
Light Ship (Dry) Weight	140,382 tonne	138,166 L.T.
Displacement @ Operating Draft	257,953 tonne	334,867 L.T.
Displacement @ Operating Draft Excluding Seawater	174,448 tonne	171,644 L.T.

flexible rubber-nylon cold water intake pipe is supported from the bottom of the hull at midships on centerline.

The space between the Second and Main Decks is utilized for fluid storage, electrical transmission and switchgear, electrical distribution equipment, auxiliary machinery, chlorinators and nitrogen and CO<sub>2</sub> storage. Wing wall spaces outboard of the main hull will be used for piping and cable runs. Ballast tanks are located at the ends of the vessel and between the warm and cold water plenums, forward and aft. The midship outboard tank spaces will be utilized for diesel fuel or ballast, as required.

The eight turbine generator sets are housed in individual enclosures on the main deck directly over the condensers. A gantry crane and two pedestal cranes will be used to handle equipment and stores between the below deck spaces and service vessels alongside. The helicopter platform and control tower are located at the end of the ship to avoid interferences.

The use of a concrete cold water pipe in lieu of the flexible rubber-nylon pipe would require an additional 16,000 tonnes of buoyancy to support the additional weight. It is anticipated that this 16,000 t of buoyancy could come from the 35,720 t margin which is presently included in the baseline design. Therefore, the present hull configuration is suitable for use with a concrete cold water pipe.

A single-point, spread mooring system is selected to position the ship plant at the New Orleans site. The extensive lateral area of the seawater discharge appendages results in high loads on a multi-point moored ship in the worst combination of extreme beam sea, current and wind. A preferred alternative is to provide for ship weathervaning in storm conditions. In head sea and wind conditions the mooring loads are substantially reduced. With the current bow-on, the warm water intake would be normal to current, serving evaporators on both sides of the ship with equal inflow conditions.

To provide weathervaning capability the ship will be moored by lines from the bow to a buoy, Fig. 6. The buoy will be positioned by a three-point spread mooring consisting of deadweight anchors, chain and nylon lines. The buoy, in addition to providing sufficient buoyancy to support the mooring line loads in the 100-year storm, will also support the electrical transmission lines to the ship and to the ocean floor. A swivel at the buoy is required to allow for rotation of the ship and transmission lines about the buoy. In the event of calm weather and zero current the tension in the mooring line will be maintained by an auxiliary thruster positioned on the ship stern. The line between ship and buoy will be of sufficient length to assure that seawater piping, buoy mooring lines, and electrical transmission riser are well separated. Cost estimates for a moored system for position control are substantially less than for dynamic positioning system, except in deep oceanic sites such as Brazil, Figure 17.

The capital cost estimates for the OTEC commercial plant using a ship platform, based on early 1978 dollars and including 10% allowance for contingency and 4% for contractor profit, are shown in Table 6. Power and energy transfer system costs are not included. The most costly systems in decreasing magnitude are the seawater system (chiefly the pumps), the cold water pipe, the hull and structure, and the position control system. The total capital cost per kilowatt is estimated to be \$690 for the reported systems. This includes \$167/kw for the seawater pumps which are sometimes included in power system costs.

Construction span for the hull is estimated to be 14 months followed by outfittings, installation of the heat exchangers, deployment to the operating site, deployment of the mooring system and installation of the cold water pipe.

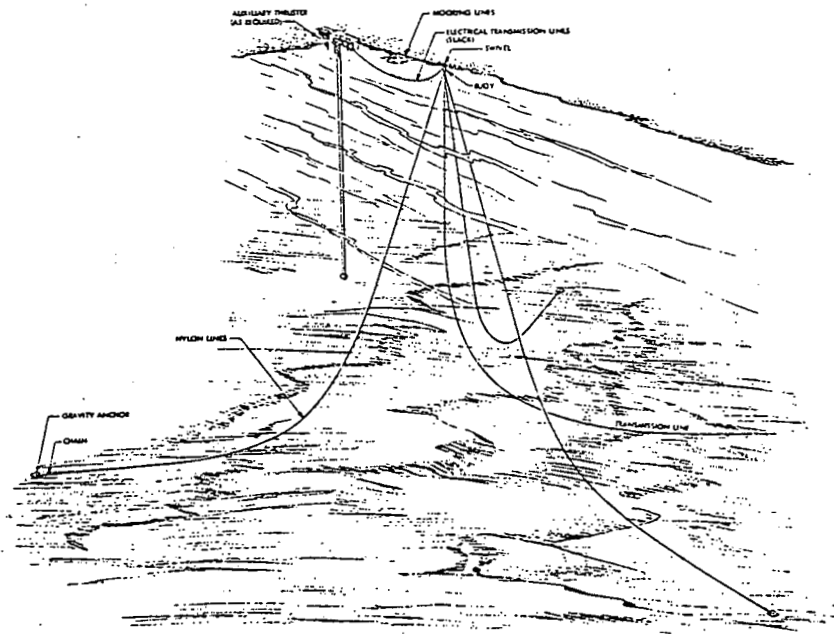


Figure 16. Conceptual design of a three-point mooring system.

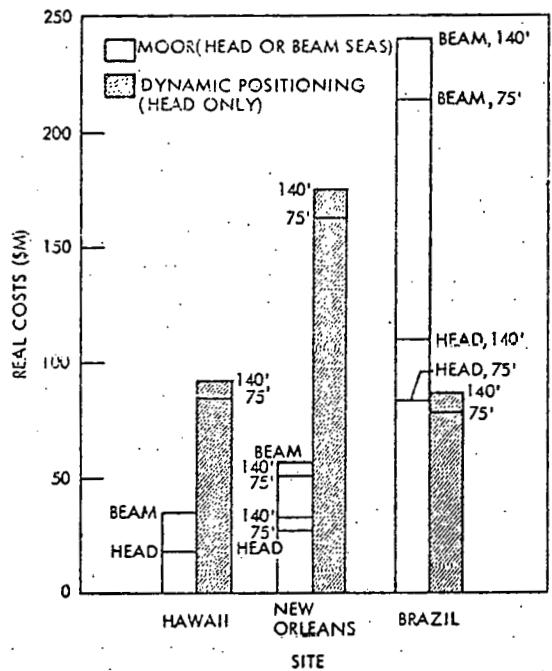


Figure 17. Costs for position control systems for ship-type OTEC commercial plant.

Table 6  
SHIP-TYPE 400 MW(e) COMMERCIAL PLANT COST SUMMARY  
(NEW ORLEANS SITE)

WBS SYSTEM	COST \$M	
	1ST UNIT	2ND THROUGH 8TH UNITS
1.0 PLATFORM SYSTEM	207.6	179.8
1.1 Platform Integration and Engineering	10.0	5.0
1.2 Hull and Structure	46.7	36.7
1.3 Position Control System	34.6	32.7
1.4 Platform Service Systems	17.6	15.6
1.5 Outfit and Furnishings	0.5	0.5
1.6 Assembly Support Services	6.8	0
1.7 Seawater System	91.3	89.3
1.8 Biological and Corrosion Control System	0	0
2.0 COLD WATER PIPE SYSTEM	64.7	53.9
5.0 SYSTEMS ENGINEERING AND INTEGRATION	5.0	2.5
6.0 SYSTEM TEST AND EVALUATION	10.0	5.0
7.0-A OPERATIONAL SUPPORT	25.0	0
8.0 DEPLOYMENT	29.7	14.7
9.0 INDUSTRIAL FACILITIES	180.0	0
10.0 ENVIRONMENTAL, LEGAL, LICENSING, REGULATION AND INSURANCE	7.5	5.0
11.0 PROJECT MANAGEMENT	22.5	15.0
<b>TOTAL CAPITAL COST</b>	<b>552.0</b>	<b>275.9</b>
<b>\$/KW(e)*</b>	<b>1,380.0</b>	<b>690.0</b>
7.0-B ANNUAL OPERATIONAL COST OF EIGHT-PLANT PARK	24.2	24.2

\* BASED ON NOMINAL PLANT RATING OF 400 MW(e) NET

## Section 6

### DESCRIPTION OF CONCEPTUAL DESIGN OF SPAR PLATFORM

This conceptual design of the spar platform for a 400 MW<sub>e</sub> (Net) OTEC commercial plant utilizing detached power modules has successfully integrated several new considerations into the design and has realized significant reductions in platform cost compared with previous spar designs. The detachable power module utilizes immersed heat exchangers. The detachable feature of the power module allows for convenient handling of the heat exchangers and power generation equipment for installation and for removal for major repairs. The immersion of the ammonia storage tanks, which are attached to the core of the spar, provides net buoyancy which contributes to the support of power conversion and transmission equipment, the cold water pipe, and to tensioning the mooring system. The use of lightweight concrete in the interior of the core, combined with elimination of permanent personnel facilities and equipment, further contribute to the reduction in size and cost of the spar-type platform. Principal characteristics are shown in Table 7. The spar-type platform consists of a central core supporting the cold water pipe and eight detachable power modules, Fig. 18. A 10-metre diameter column extends through the water surface, providing access to the core. Each module consists of a main cylinder which houses the power plant components with attached cylinders at each end which support the sea water pumps and ducts. The module and core are connected at the cold water inlet and at the turbo-generator space access. The core and modules are constructed from lightweight concrete. The large height of the core requires a two-stage construction process which starts in a graving dock with a 33 ft(10m) floatout draft, and is completed in a deep (98 ft (30m)) wet dock.

The warm water enters each module near the water surface, flows vertically downward through the pumps and evaporators, and discharges horizontally at 45 metres below the surface. The cold water enters each module from the distribution plenum at the base of the central core. It then flows into the

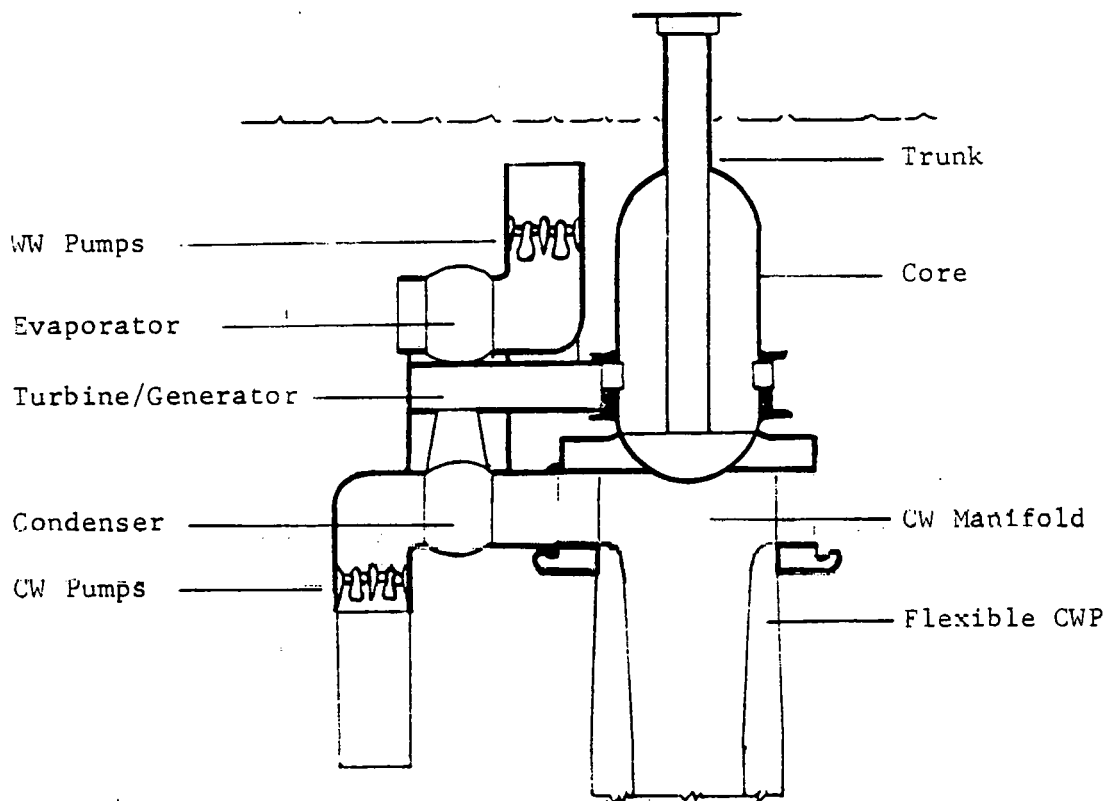


Fig. 18 Configuration of spar-type OTEC commercial plant. (One module shown.)

Table 7

Principal Characteristics of Spar-Type OTEC Commercial Plant  
400 MW<sub>e</sub> Net, New Orleans

Width Overall	158 m	518 ft
Height Overall (Excluding CWP and Cold Water Outlet Pipe extension)	139 m	456 ft
Operating Draft (Excluding CWP and Cold Water Outlet Pipe extension)	114 m	374 ft
Light Ship (Dry) Weight (Including CWP)	244,000 tonne	240,157 LT
Displacement at Operating Draft	438,000 tonne	431,102 LT
Displacement at Operating Draft Excluding Seawater	256,000 tonne	251,969 LT

condensers, and through the sea water pumps to exit downward at a depth of 150 metres. Valves which close off the plenum to provide buoyancy during deployment are closed during removal of a power module so that the other modules can continue to operate.

A comparison of three point spread mooring and dynamic positioning system costs indicates that for Hawaii and New Orleans the mooring system is approximately one third of the cost of a dynamic positioning system. The estimated cost for the three point mooring for New Orleans is \$36.8M.

Another approach to mooring the spar is to provide excess buoyancy at the operating draft and to provide the reaction through a tension mooring leg, Fig. 19. The spar is suited to this concept because of the low waterplane area in comparison with ships. The cold water pipe can be used to provide the tension leg so that there is a reduction in the length of the mooring lines by attachment to the inlet end of the pipe. A further advantage of this approach is that the mooring lines will be separated from the platform so that there is lower risk of entangling the electrical transmission lines and the pipe with the mooring lines. The tension leg mooring imposes an additional load on the cold water pipe which must now carry the drag force on the platform. The cost of the tension leg mooring system is \$14M initially, and including replacement costs it becomes \$30.7M, Fig. 20.

Estimated costs for the 400MW<sub>e</sub> (Net) commercial plant using the spar platform with detachable power modules are presented in Table 8. The sea water system is the most costly system followed by the hull & structure, the cold water pipe, and the position control system in decreasing

The construction schedule for the core requires 9 months in the graving dock, and an additional 14 months in the deep, wet dock.

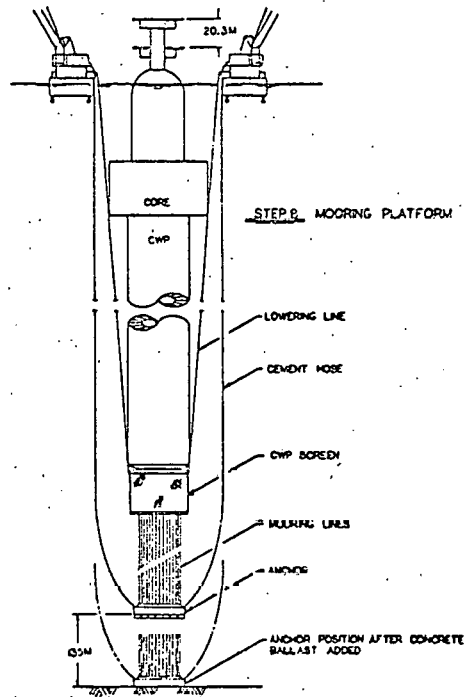


Figure 19. Conceptual approach to tension-leg mooring installation.

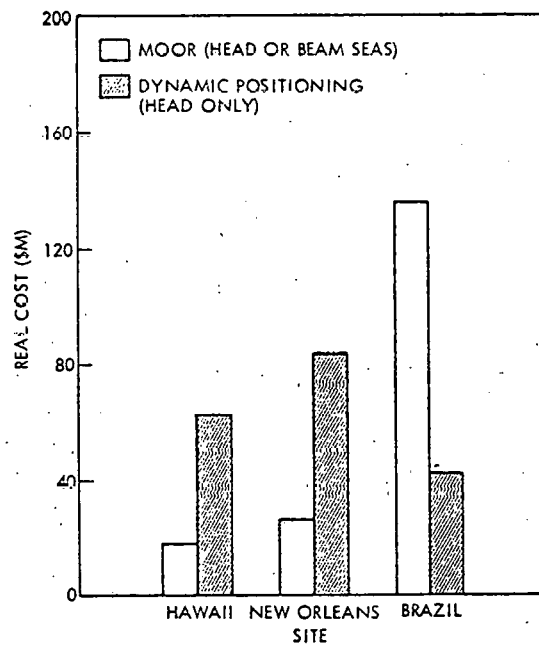


Figure 20. Costs for position control systems for spar-type OTEC commercial plant.

Table 8  
 SPAR-TYPE 400 MW(e) COMMERCIAL PLANT COST SUMMARY  
 (NEW ORLEANS SITE)

WBS SYSTEM	COST \$M	
	1ST UNIT	2ND THROUGH 8TH UNITS
1.0 PLATFORM SYSTEM	262.4	228.6
1.1 Platform Integration and Engineering	10.0	5.0
1.2 Hull and Structure	79.5	69.5
1.3 Position Control System	32.7	30.7
1.4 Platform Service Systems	35.6	33.6
1.5 Outfit and Furnishings	0.5	0.5
1.6 Assembly Support Services	12.8	0
1.7 Seawater System	91.3	89.3
1.8 Biological and Corrosion Control System	0	0
2.0 COLD WATER PIPE SYSTEM	62.4	51.6
5.0 SYSTEMS ENGINEERING AND INTEGRATION	5.0	2.5
6.0 SYSTEM TEST AND EVALUATION	10.0	5.0
7.0-A OPERATIONAL SUPPORT	25.0	0
8.0 DEPLOYMENT	15.7	12.7
9.0 INDUSTRIAL FACILITIES	200.0	0
10.0 ENVIRONMENTAL, LEGAL, LICENSING, REGULATION AND INSURANCE	7.5	5.0
11.0 PROJECT MANAGEMENT	22.5	15.0
TOTAL CAPITAL COST	610.5	320.4
\$/KW(e)*	1,526.0	801.0
7.0-B ANNUAL OPERATIONAL COST OF EIGHT-PLANT PARK	24.2	24.2

\* BASED ON NOMINAL PLANT RATING OF 400 MW(e) NET

## Section 7

### SENSITIVITY TO SITE

Three major platform-related factors are affected by the selection of the operational site for the commercial plant. These are the motions of the platform, the costs of the platform, and the average annual output of the power system. A summary of these factors for the two platform configurations for the sites of New Orleans, Hawaii, and Brazil are presented in Table 9. The depth of the cold water intake is 1000m (3281 ft).

The motions of two platforms estimated for extreme (survival) conditions for the three sites indicate that the ship headed into the sea undergoes 2.5 times the pitch motion of the spar. The pitch motion is greatest (6.2 degrees for the ship and 2.5 degrees for the spar) at New Orleans and least for the Brazil site.

Capital costs for commercial OTEC plants with nominal 400 MW<sub>e</sub> net output, excluding power and energy transfer systems, primarily reflect the change in cost for the position control system for each site. The ship cost varies 26 percent among the sites, while the spar costs vary by 7 percent.

The annual average output of the plants based upon assumed gross design output of the power system of 520 MW<sub>e</sub> (=65x8) ranged from a low of 364 MW<sub>e</sub> for the ship at New Orleans to 448 MW<sub>e</sub> for the spar at Brazil. The power system for this case is based on a design temperature differential of 40 degrees F. The spar is about 1 percent more efficient than the ship concept because of lower parasitic power requirements in the sea water system.

The ratio of capital cost per annual average output for the commercial plants varies 16 percent among the three sites for the ship and 18 percent for the spar.

Table 9  
 SENSITIVITY TO OPERATIONAL SITE  
 (Intake depth of cold water pipe is 1000M (3281 ft))

	<u>Platform</u>		
	<u>Site</u>	<u>Ship</u>	<u>Spar</u>
<u>Platform Motions in Extreme Seas</u>		<u>Significant Amplitude of Pitch angle - degrees</u>	
	New Orlean ( $H_5=58.1$ ft)	6.2 (Head)	2.5
	Hawaii ( $H_5=35.9$ ft)	2.6 (Head)	1.0
	Brazil ( $H_5=29$ ft)	1.8 (Head)	0.7
<u>Capital Costs</u> *(for each 2nd to 8th Units)		<u>Millions of Dollars (1978)</u>	
	New Orleans (Moored)	275.9 (Head)	320.4
	Hawaii (Moored)	261.2 (Head)	306.7
	Brazil (Dyn. Pos.)	327.2 (Head)	330.7
<u>Annual Average Output of Plant (<math>\Delta t</math> Design=40°F)</u> (Assuming 65x8=520 $MW_e$ (gross))		<u><math>MW_e</math> (Net) average</u>	
	New Orleans	363.7	366.6
	Hawaii	378.3	381.4
	Brazil	440.0	448.0
<u>Capital Cost per Annual Average Output</u> *,		<u>\$/<math>kW_e</math> average</u>	
	New Orleans	759	873
	Hawaii	690	802
	Brazil	736	738

\* Excluding costs of power and energy transfer systems.

Section 8  
CONCLUSIONS AND RECOMMENDATIONS

The following conclusions and recommendations were derived in this study.

1. The cost to construct hulls for OTEC platforms to contain internally-installed power system components are estimated to be significantly less (about 32%) in concrete than in steel.
2. Sea water ducts inside a platform hull are very expensive. Minimum lengths and optimized diameters of sea water ducts are recommended for economic and weight considerations. Immersed ducts are also recommended to reduce cost and weight.
3. The sea water pumps are a major cost item of the platform. Trade studies for arrangements, reliability, multiple units, and cost are inconclusive at this conceptual design stage of the platform and power systems.
4. Structural flexibility is required in cold water pipes to minimize the impact of platform motions on the wall thickness, weight and cost of the pipe. Replacement costs may be a significant consideration in pipe optimization.
5. A concrete cold water pipe equipped with flexible joints is the lowest cost to construct and is very insensitive to design sea conditions. Deployment costs for this pipe are 75 percent of construction costs. Its large weight has an impact on buoyancy requirements on the platform.
6. An inflated rubber/fabric cold water pipe is apparently slightly more cost effective than the concrete pipe if long life can be attained. Platform impact and deployment costs are minimal with this type of pipe.
7. Four platform configurations seem to be most desirable for OTEC commercial plants. These are the detached and internal spar, the circular barge, and the ship.
8. Three platform configurations are less desirable for OTEC commercial plants. These are the submarine, the tuned sphere, and the semisubmersible.
9. Hulls for OTEC platforms can be optimized by utilizing the inherent buoyancy obtained by immersion of components of the power system, chiefly the heat exchangers and the ammonia storage tanks

10. A conceptual design of a ship-type platform for a 400 MWe (net) OTEC commercial plant has an estimated capital cost per nominal net output of 690 \$/KW for a New Orleans site.
11. A spar-type platform with detachable power modules has an estimated cost of 801 \$/KW nominal for the New Orleans site.
12. The sensitivity of these conceptual designs to three sites (New Orleans, Hawaii, Brazil) shows a large (3.5:1) variation among the sites for both platforms for motions in extreme seas, and 26 percent variation in capital cost for the ship and 7 percent variation for the spar among the sites.
13. It is recommended that a demonstration unit for an OTEC plant have an output of about 25 MWe to meet the needs of both small and large system users. Demonstration of full scale components (pumps, thrusters, anchors, etc.) is recommended. Demonstration of the energy transfer system (electrical transmission or chemical conversion and shipment) must be included. Operations personnel should represent potential OTEC users.

Section 9

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