NOAA Technical Report OTES 4

OTEC Mooring System Development: Recent Accomplishments

Rockville, Md.
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U.S. DEPARTMENT OF COMMERCE
National Oceanic and Atmospheric Administration
Ocean Technology and Engineering Services

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OTEC MOORING SYSTEM DEVELOPMENT: RECENT ACCOMPLISHMENTS

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ABSTRACT. The mooring system for a floating OTEC platform consists of a seafloor foundation, a platform foundation, and a connecting line. This paper introduces the OTEC mooring system with a brief historical overview, reviews developmental work accomplished during the past year, and then presents a new look at life cycle costs for an example mooring system.

Since June 1980, a significant effort within the OTEC Program has been directed toward the further development of mooring systems. The effort has included work leading to a better understanding of anchoring capabilities and problems, refinement of an existing mooring analytical model, a review of OTEC past mooring designs, and the production of a mooring system technology development plan. A major finding of the past year was a new upward estimate of mooring system lifetime costs as a result of downward-revised estimates of wire rope service life.

I. INTRODUCTION

For any floating moored OTEC plant, the mooring system is an element of primary importance. This importance has been recognized by the OTEC community, and a substantial effort has been -- and continues to be -- invested in the extension of the present state of the art to a level sufficient for use in holding a floating OTEC plant on station at water depths of several thousand feet. In the following pages, we will examine advancements in mooring system state-of-the-art during the course of the past year. Also, we will present an example of estimated life cycle costs for a pilot plant mooring system, including some substantial cost increases brought about by considerations of inspection, maintenance, and repair (IM&R).

For the purposes of this presentation, the mooring system is composed of three elements: seafloor foundation, platform foundation, and connecting line. The seafloor foundation may be a gravity, pile, or drag embedment type anchor. The platform foundation consists of fairleads and line handling gear. The connecting line may be composed of wire, synthetic rope, chain, or a combination of these. Only floating OTEC plants are considered here; thus, the supporting structure of a shelf-mounted plant or guyed tower plant is not considered, although such structures do parallel a mooring system in their function.

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II. HISTORICAL CONTEXT

The functions of an OTEC mooring system have remained unchanged. They are to hold the platform within a specified watch circle during normal operating conditions and to hold the platform on site during the stress of a "100-year storm." The mooring system is meant to function for a multi-year (e.g., 30 years) service life. Construction, installation, IM&R, and retrieval must be feasible technically and within a cost compatible with the economics of the OTEC plant operation.

Until recently, the technical development of the mooring system has been overshadowed by work on the platform and cold water pipe (CWP). However, two large studies and several related studies have been completed on mooring systems for the OTEC pilot plant. The two large studies were conducted by M. Rosenblatt and Son, Inc., (1)* and Lockheed Missiles and Space Company (2), during 1979. Both studies resulted in preliminary designs of mooring systems for the OTEC pilot plant. Design requirements, conceptual design, preliminary design, development and testing recommendations, a cost-time analysis, and recommendations for a commercial OTEC plant mooring system were included in each study. Rosenblatt developed a 12-leg multi anchor leg (MAL) mooring system for the barge shaped plant (figure 1) and an 8-leg MAL mooring system for a spar-shaped plant (figure 2). Lockheed considered an 8-leg MAL mooring for the barge and a tension anchor leg (TAL) mooring for the spar (figures 1 and 3). A concise review of both studies is presented in references 3, 9, and 10.

In addition, a number of studies addressed other aspects of OTEC mooring systems. One such study (4), by Gibbs and Cox, Inc., presents a baseline design of a 40-MW spar pilot plant moored by a TAL mooring system which is integral with the CWP. Hoffman Maritime Consultants, Inc., conducted a study (5) which outlines requirements for the formulation of an analytical model which could be used to provide a quantitative comparision and assessment of candidate mooring systems. The IM&R aspect of mooring systems is included in a study (6) by Brown and Root Development, Inc. In their large systems construction techniques report (7), Delta Marine Consultants, BV, includes consideration of various MAL mooring systems for different types of 400-MW commercial OTEC platforms.

III. WORK DURING THE PAST YEAR

Since June 1980, a significant effort within the OTEC Program has been directed toward the development of mooring systems. This effort has included work to further understand mooring requirements, capabilities, and problem areas; refinement of an existing mooring analytical model; review of past OTEC mooring designs; and the production of a mooring system technology development plan. A major finding of the year was the upward estimate of mooring system lifetime costs due to lower expectations for mooring system component life. The paragraphs below provide an overview:

*Numbers in parentheses refer to references at the end of the text.

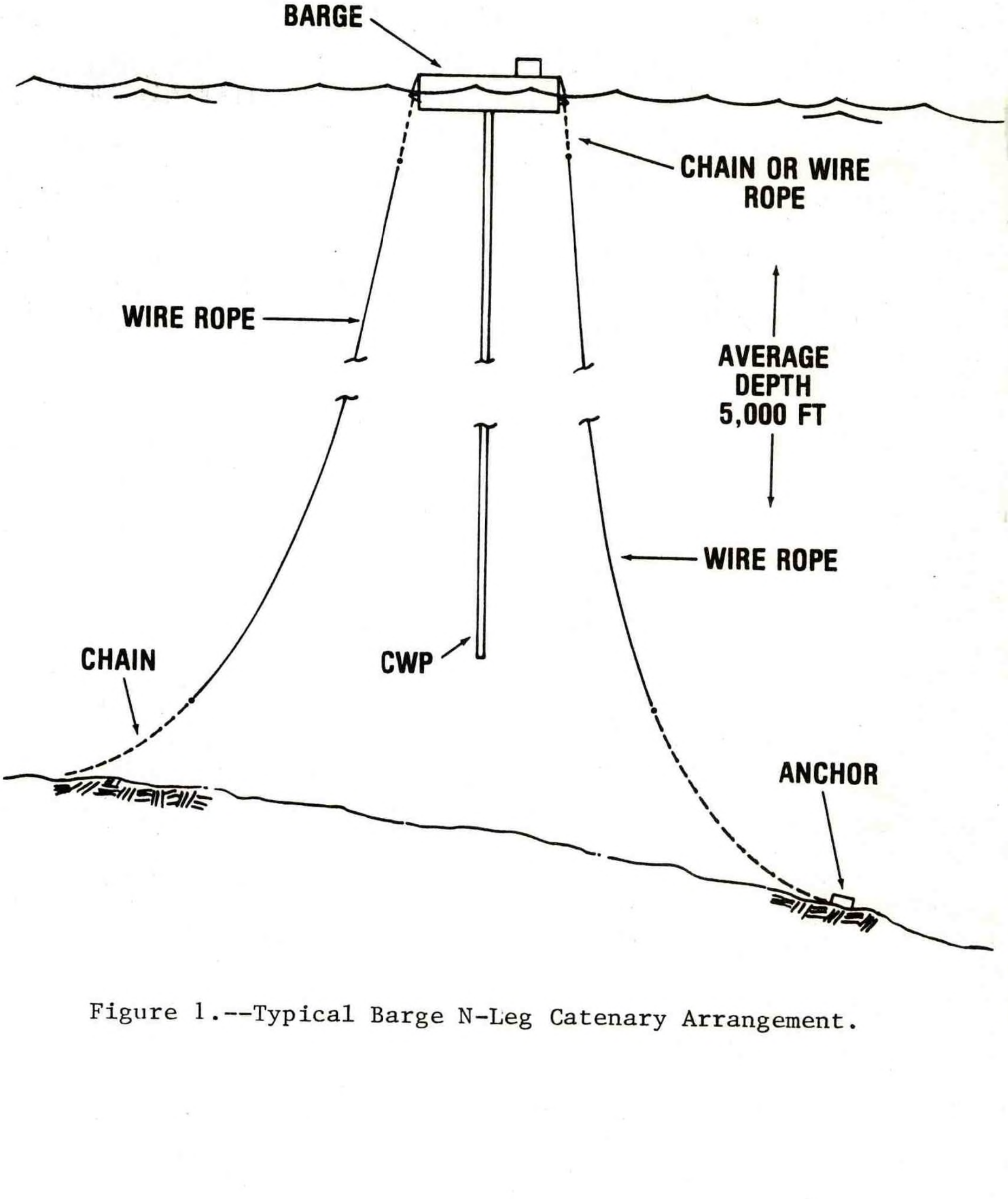

Figure 1.--Typical Barge N-Leg Catenary Arrangement.

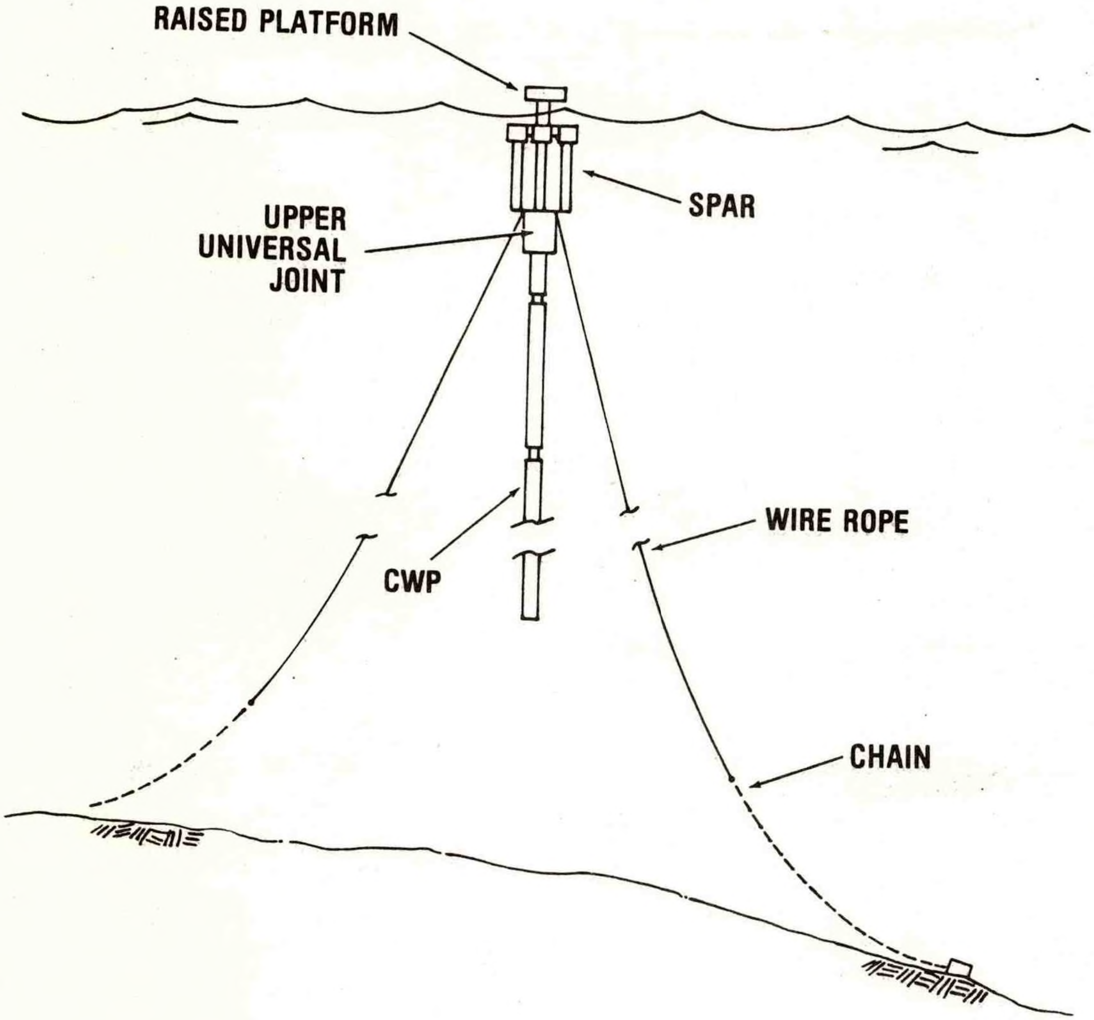

Figure 2.--Rosenblatt Spar 8-Leg Mal Arrangement.

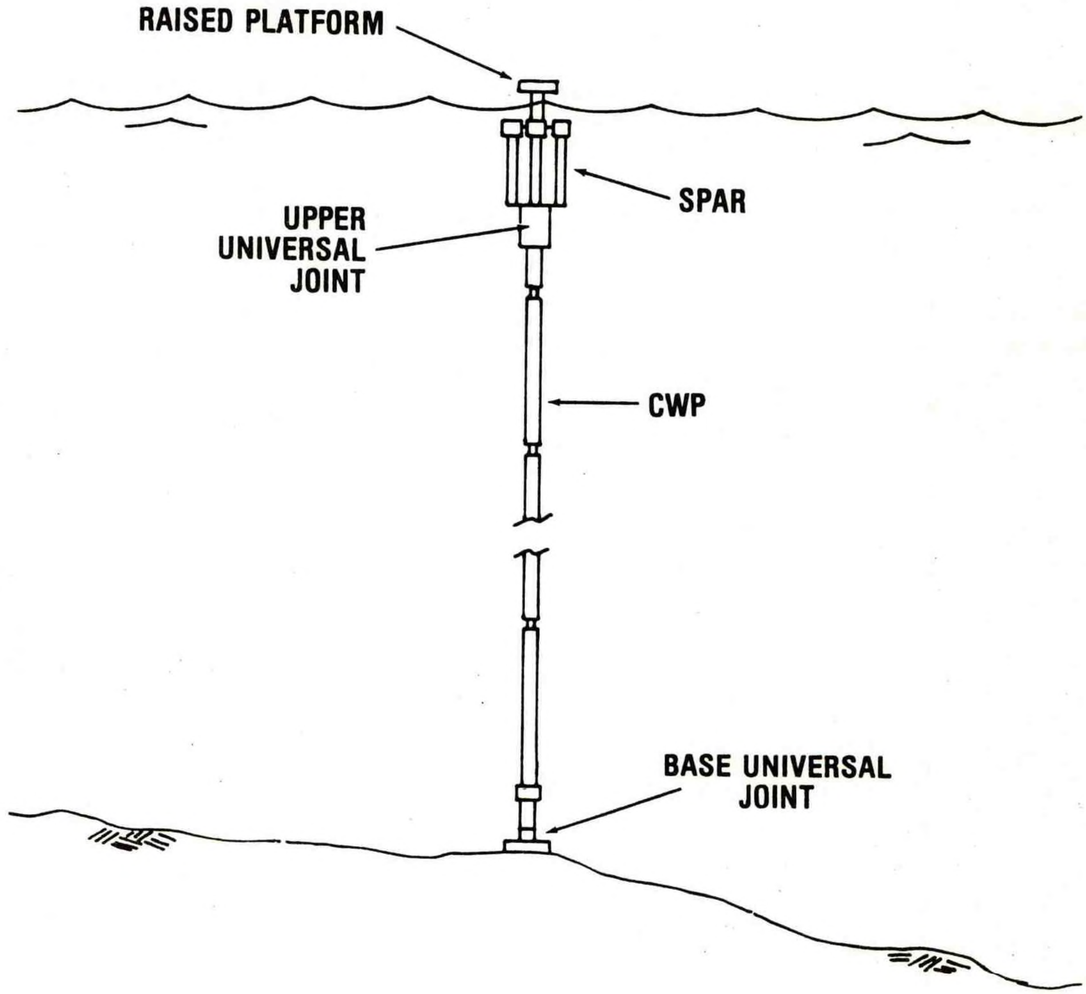

Figure 3.--Lockheed Spar TAL Arrangement.

In June 1980, just as the Seventh Ocean Engineering Conference came to a close, an interagency anchoring workshop was held. The workshop was attended by 45 representatives of government, industry, and academia. The object was to "assist in the development of geotechnical requirements for OTEC anchoring" (8). Among the recommendations were increased Department of Energy support for site-specific geological/geophysical/geotechnical surveys, the development of an analytical model to determine the relationship between the holding power of an anchor and the degree of seafloor slope, selection of an advisory panel to deal with anchoring, and assurance that the mooring system for the OTEC pilot plant be conservative and well instrumented.

In late 1980 and early 1981, a survey was made of existing mooring analytical models, with a view toward acquiring such a model and modifying it as required for use as an OTEC design tool. A model has been leased and several test runs made using a typical OTEC MAL system. This model appears appropriate for future use in OTEC mooring design. Results of these preliminary runs have been used in developing the example mooring system addressed later in this paper.

Det norske Veritas (DnV) carried out a comprehensive review (9, 10, 11) of the mooring system designs which were developed by M. Rosenblatt and Sons, Lockheed Missiles and Space Company, Gibbs and Cox, and Delta Marine Consultants. DnV recommended that MAL moors be considered for final design phases and concluded that, in general, the MAL designs presented by Rosenblatt and Lockheed provide a sound basis for the final design phase of OTEC mooring systems in spite of a lack of uniform design criteria. In reference (9), DnV recommended a consistent set of design criteria for OTEC mooring systems. The Lockheed TAL solution was not considered reliable, "mainly due to lack of redundancy, vulnerable combination of SKSS (i.e., mooring system) and CWP, and uncertainties related to universal jounts and CWP buoyancy system (10, p.7)." The Gibbs and Cox TAL mooring system was not considered sufficiently reliable, again, because lack of redundancy was considered a serious drawback (11, p. 1). DnV believed that the IM&R costs appeared low. Because of inadequacies in the state-of-the art of deep water mooring techniques and materials, DnV recommended a conservative approach to mooring system design. As a result of the conservatism necessary to overcome unknowns, the OTEC mooring system life cycle cost estimates will increase dramatically over those stated in the above studies.

Det norske Veritas also conducted a study (12) concerned with the requirements for design, fabrication, and IM&R for the OTEC pilot plant platform, CWP, and mooring systems. This study established minimum requirements for OTEC plant structural elements reflecting relevant codes and regulations, supplemented as necessary, to obtain and maintain an acceptable and consistent level of safety from the start of design through construction, operation, and eventual removal of the structure.

Within the NOAA OTEC Program, Giannotti and Associates has produced a mooring system technology development plan (13). This plan is wide in scope, covering government and industry contributions to mooring system technology over the next 5 years.

In the years since the inception of the modern OTEC program, a heavy emphasis has been placed on using applicable technology from the offshore petroleum industry. This past year, there were some direct links between the OTEC community and the offshore companies, especially in the area of shelf-mounted OTEC designs (14). Also, certain ongoing work by the offshore community has a direct bearing on OTEC mooring systems. Tension leg platforms (TLP's) and tension piles are two prime examples of such work.

In the offshore community, considerable work has been directed toward the development of TLP's, especially as offshore oil production progresses into ever-deeper waters. Under these conditions, TLP's are becoming economically more attractive than the massive steel and concrete fixed platforms. The two advantages of the TLP's which make them attractive for offshore oil production also make them attractive for OTEC energy production: (a) mooring system cost should change relatively little as water depth increases and (b) the moor can be detached from the seafloor anchors to move the floating platform to a new location (e.g. shipyard overhaul site or new work site). Plans call for the first TLP to be in use by 1984 in the Hutton Field, 90 miles off the Scottish Coast in 485 ft of water (15, 16). It is expected that this type of platform will eventually extend oil production into waters ranging to 2,000 ft and possibly as much as 6,000 ft. Figure 4 shows an example of a TLP. One important point to note is the multiple tension legs of the moor; these ensure a redundancy in the system and can be periodically drawn up into the platform for inspection, repair, or replacement.

Another area of interest which encompasses both the OTEC and the offshore communities is the subject of tension piles. These form an appropriate seafloor anchor for catenary moors and for the new TAL's, and their development has progressed during the past year. For example, Taylor Woodrow installed intrumented steel circular piles 10-m long at a field site. The piles were placed under vertical and horizontal loading up to the forces of a simulated storm. In addition to the field test, complementary--less expensive--laboratory tests were conducted. The data are now being processed and will help in the design of future pile anchoring systems (17). Other tension pile tests are being carried out by BP Trading, Ltd., and BNOC, Ltd., for the British Department of Energy. The objective of the program, carried out on well-characterized test beds, is to measure the performance of 1/10-scaled piles under vertical and horizontal loading in order to formulate design methods for at-sea tension pile anchors. Piles varied in diameter in this test from 100 mm to 300 mm (18). In addition, BSP International Foundations, Ltd., tested a 15 meter-tonne prototype of an underwater pile-driving hammer in 150 m of water in Loch Linnhe, Scotland. The modular system is designed to have a maximum energy of 200 meter-tonnes and a maximum submerged depth of 300 m. Future development is to increase the depth to 1,000 m and possibly beyond (19).

From this sampling of mooring system development activity, it is evident that advancements are being made toward innovative designs, larger systems, and deeper waters and that steady progress continues toward solving the important design unknowns of permanent, open-ocean moorings for pilot and commercial OTEC plants.

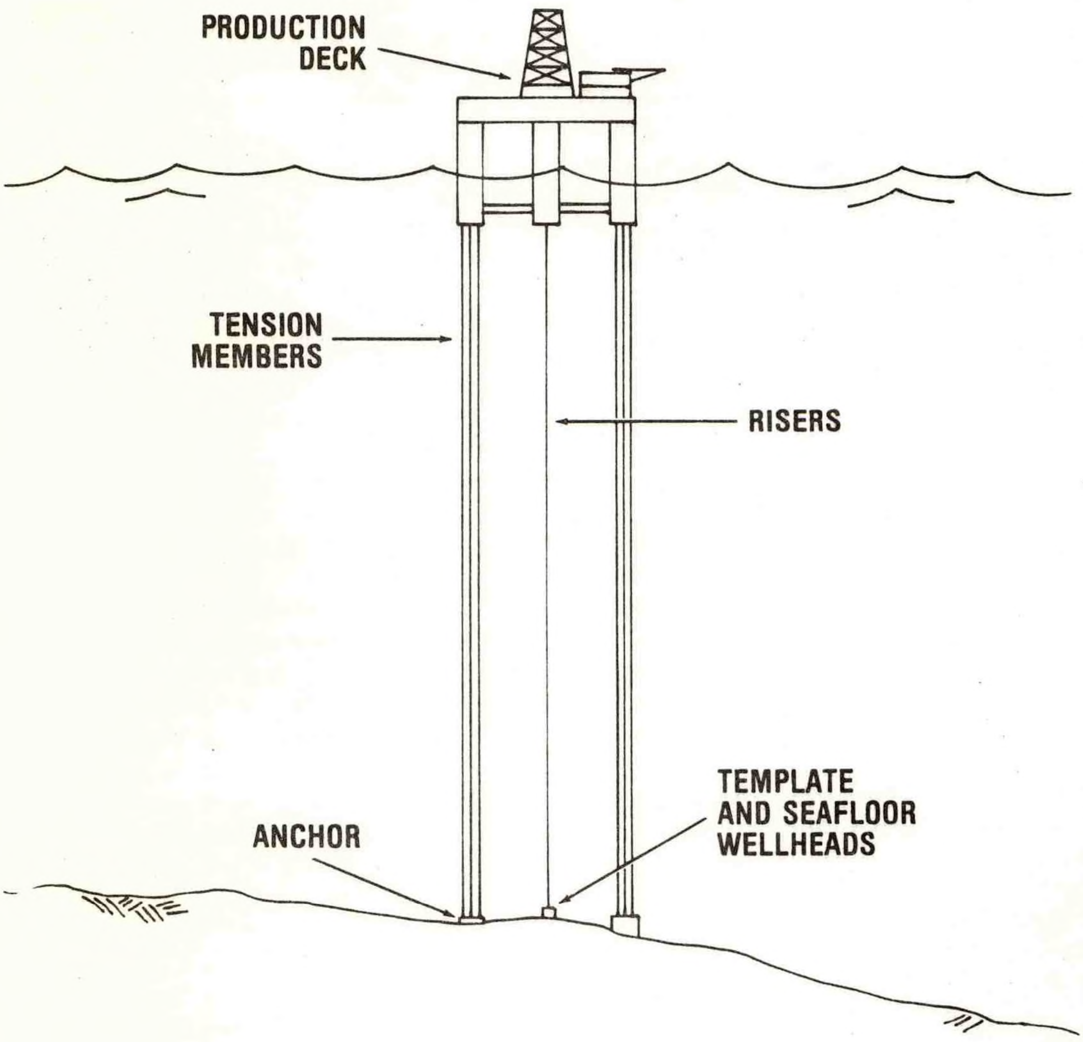

Figure 4.--Tension Leg Platform (TLP).

IV. A NEW LOOK AT LIFE CYCLE COSTS

Introduction

Instead of presenting a detailed description of all the mooring system work of the past year, we have given a brief overview only. References are provided for those who would like to study further. In our view, a synthesis of the last year's major-impact studies is of more value than an in-depth review. Such a synthesis offers insight into the cumulative effects of the studies and illustrates today's state of development of the OTEC mooring system.

Our synthesis is attained through computing the life cylce costs for the mooring system of a closed cycle OTEC pilot plant. We will focus on one specific example mooring system in order to provide more depth to the analysis, although we recognize this approach does not fully cover various other OTEC designs under present consideration.

Description of Example Mooring System

Our example is a pilot plant composed of a Johns Hopkins University Applied Physics Laboratory (APL) concrete barge, a melded version of the Rosenblatt and Lockheed catenary mooring systems, and a choice of one of three anchor types.

The APL barge was chosen because it represents an established baseline approach to the moored floating OTEC plant. Also, through analyses and model testing, a good deal is known about its naval architectural characteristics, seakeeping behavior, and the effect that environmental forces will have on the mooring system. In order to have a baseline design common to past work, the June 1979 barge version (20) is considered rather than progressing to the later design with improved seakeeping characteristics presented by Giannotti and Associates (21).

The June 1979 version of the APL barge is shown in Figure 5. This barge has the following characteristics:

Length overall	453 ft
Beam (hull)	140 ft (178 ft at warm water pumps)
Operating draft	65 ft
Operating freeboard (to upper deck)	24 ft
Gross weight (including ballast)	97,109 long tons

The mooring system connecting line uses ideas from the mooring studies conducted by Rosenblatt (1) and Lockheed (2) but incorporates technical recommendations and life cycle cost considerations presented in a recent study by Det norske Veritas (9). The connecting line portion of the moor is a MAL catenary type. Figure 6 illustrates one of the 12 identical (except for length, because of a sloping seafloor) legs, and table 1 gives a description of component characteristics.

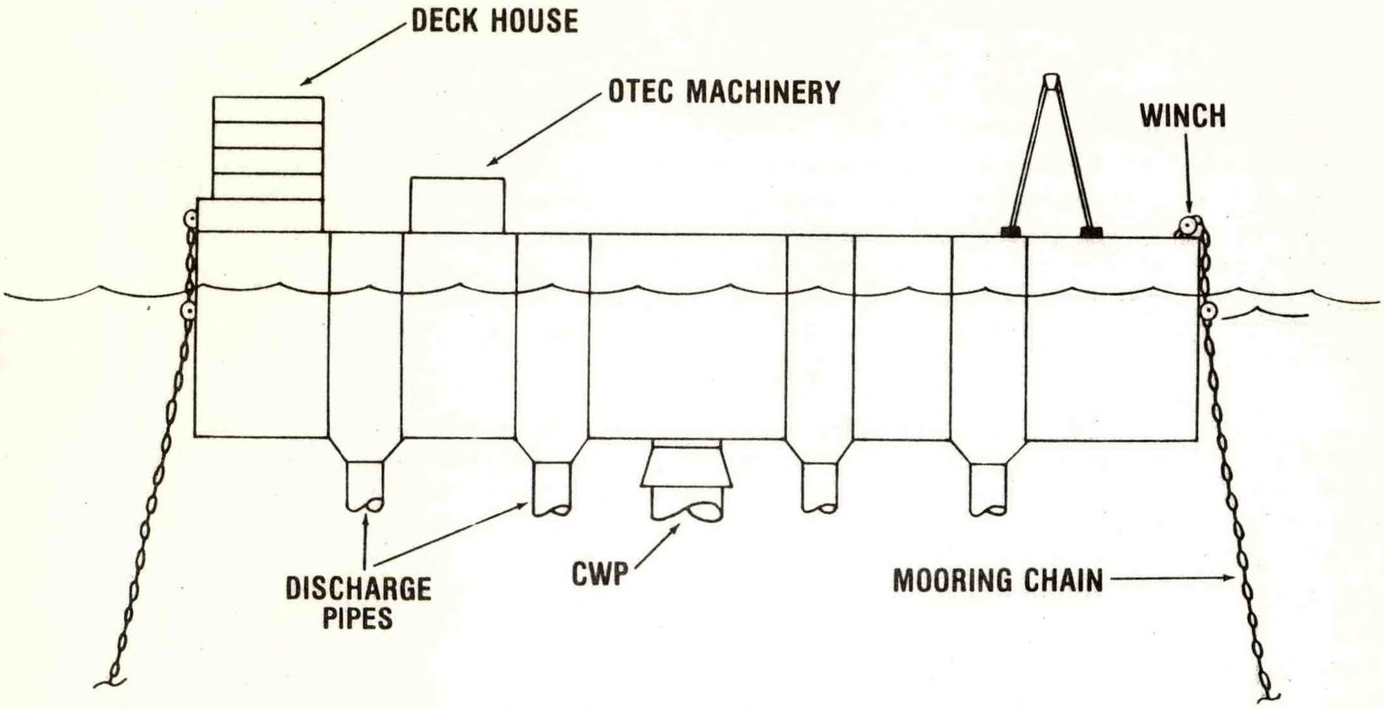

Figure 5.--Elevation of APL 40-MW Pilot Plant Barge.

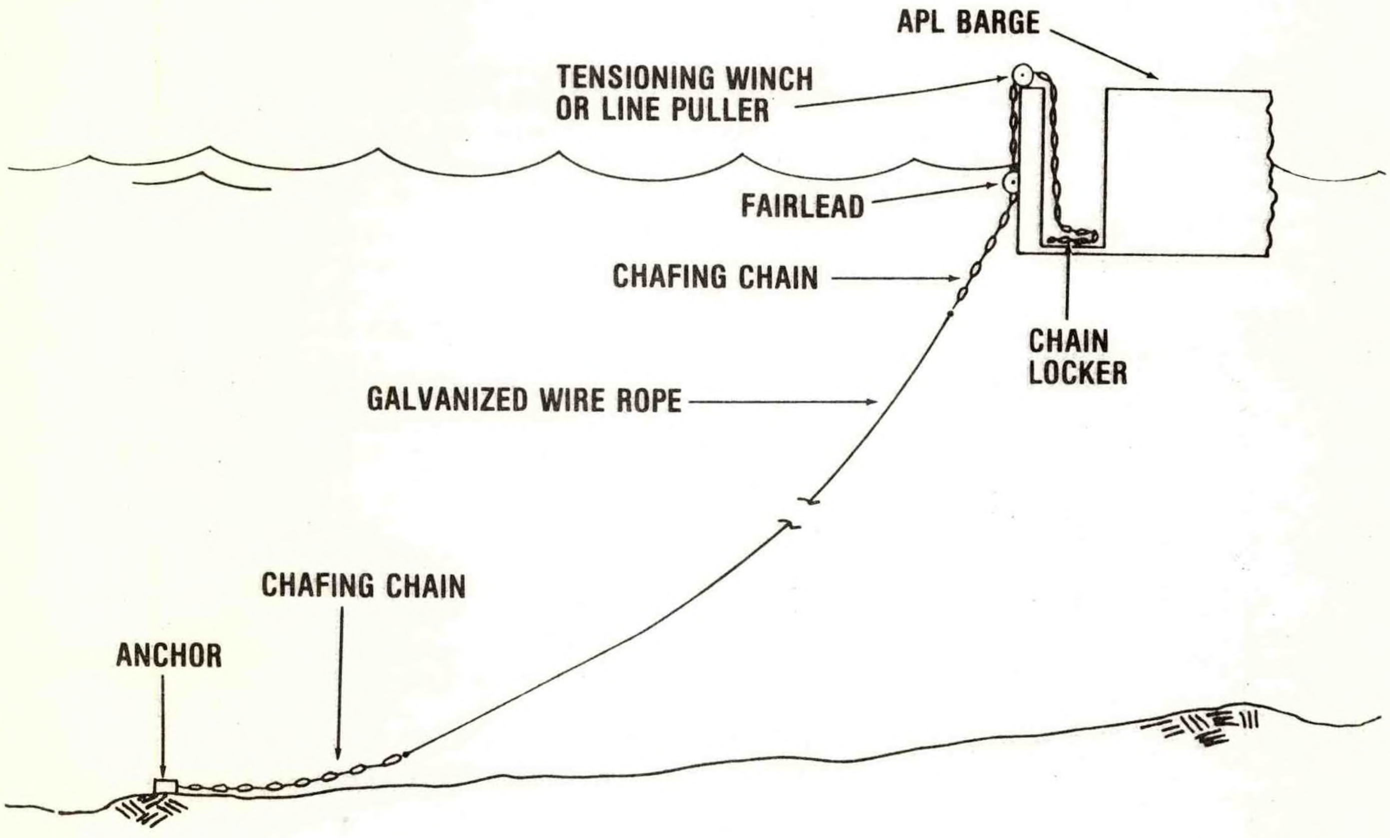

Figure 6.--Typical Leg of Example Mooring System.

Table 1. Leg Description for Example Mooring System

Number of mooring legs	12
Wire rope characteristics	Nominal diameter: 5 1/2 in. Type: 8x37 IWRC unit lay Material: Monitor AA steel (galvanized) Breaking strength: 2,567,000 lb Weight: (Dry) 64.2 lb/ft, (Wet) 53.3lb/ft Blocked with petrolatum based grease or synthetic infill
Wire rope lengths	(Lines 1, 2, 11, 12): 5,000 ft (Lines 3, 4, 9, 10): 4,500 ft (Lines 5, 6, 7, 8): 5,500 ft
Chain characteristics	Type: 4 1/2 in. ORQ stud link chain Breaking Strength: 2,508,000 lb Weight: (Dry) 205 lb/ft, (Wet) 178 lb/ft
Chain lengths	(Lines 1, 2, 11, 12): 5,000 ft (Lines 3, 4, 9, 10): 5,500ft (Lines 5, 6, 7, 8): 4,500 ft

Note: Wire and chain lengths are for 5,200 ft water depth under platform and 6° average seafloor slope. Each anchor line has a 300 foot chafing chain at the platform interface; this chain is the same type as is used for the sea floor segment.

We investigated three distinct types of anchors: drag embedment, deadweight, and pile. Different anchor types are appropriate for different seafloor conditions and, if necessary, all three could be used in a single mooring system. Several typical drag embedment anchors are shown in figure 7. The anchors include a Bruce type, weighing 50,000 lb in air and possessing a holding force of 997,000 lb in a calcareous ooze composed of sandy silt and clayey silt (2). Also included are a Stato Anchor and a Stevin Anchor. The deadweight anchor is shown in figure 8. This anchor is fabricated of structural steel beams and plates and ballasted with concrete or mud. The pile anchor is shown schematically in figure 9. This anchor is composed of a number of steel piles connected to a common template. The mooring leg chain is attached to the template.

Computer Analysis of Example Mooring System

The example mooring system was subjected to a computer analysis using a quasi-static program (22), with environmental conditions as shown in table 2. The program, FLOATMOOR, was developed by B. W. Oppenheim, who also ran this computer analysis. We used the analysis to obtain load data to compare with the Rosenblatt results (2) and to check whether our example mooring system possessed adequate strength to withstand survival condition forces. While a complete analysis of the results of this program has not yet been accomplished, preliminary results are available and will be discussed.

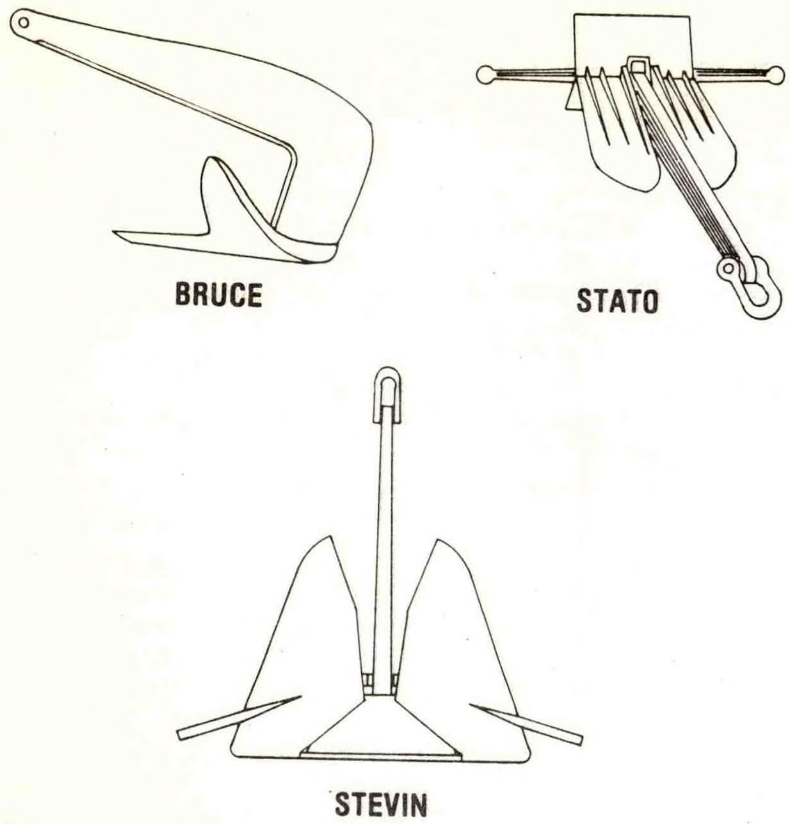

Figure 7.--Drag Embedment Anchors.

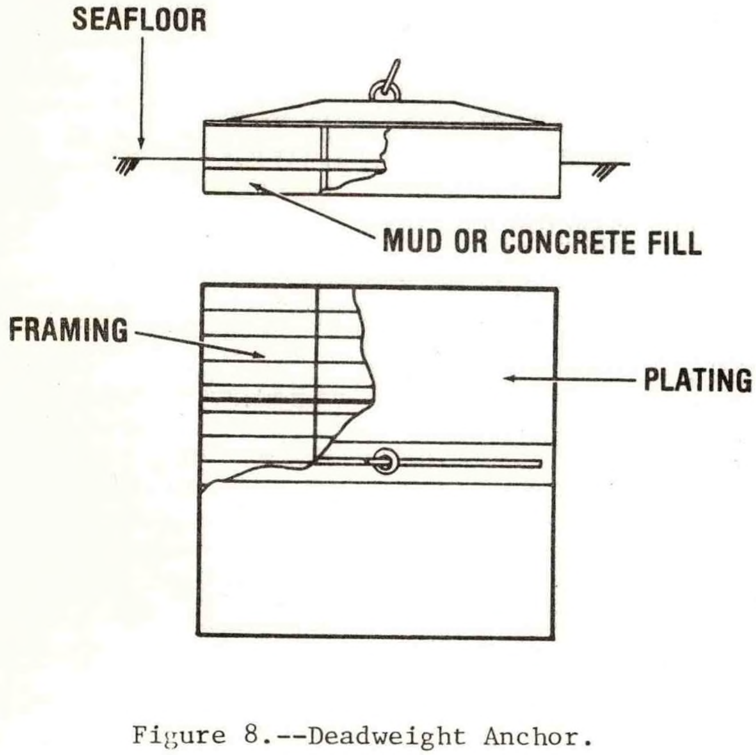

Figure 8.--Deadweight Anchor.

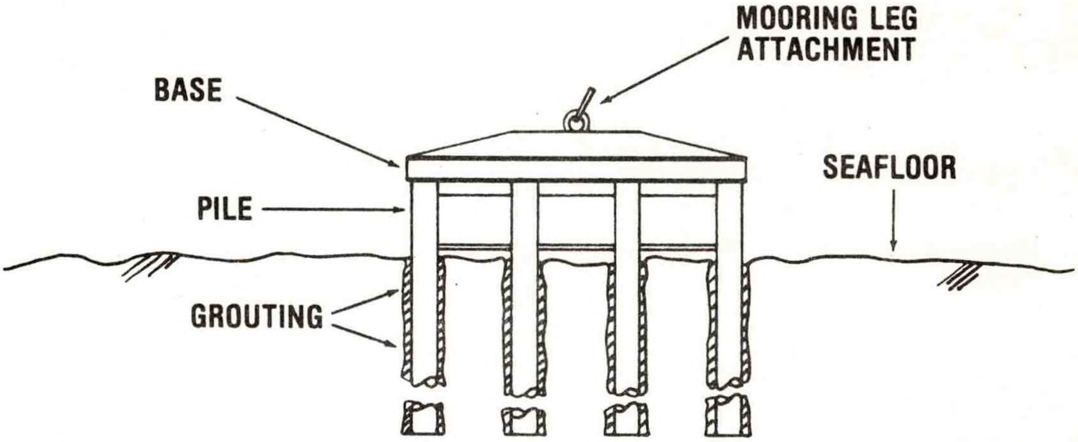

Figure 9.--Pile Anchor Schematic.

A fairly close agreement exists between the Rosenblatt and FLOATMOOR analyses. For maximum line tensions at the platform fairlead, Rosenblatt gave values of 858 kips for the operational condition and 1,260 kips for the survival condition. FLOATMOOR gave values of 870 and 1,304 kips, respectively. These figures agree within several percent.

With respect to adequate strength, the guidelines given by DnV (9) were used for the mooring line tension and the anchor holding force. In each case, the FLOATMOOR results were used. For mooring lines, a factor of safety (FS) of 2 was recommended. Our FS is 2,567 kips/1,304 kips = 1.97 and is essentially sufficient. For the anchor, an FS of 1.5 to 2 was recommended. As our available holding force, we used the 997 kips of the Bruce Anchor and used a figure of 1,132 kips (from FLOATMOOR results) for the required survival holding force. Our FS is 997 kips/1,132 kips = 0.88. Thus, the anchor size should be increased or tandem anchors used to give an increased available holding force. Since the following analysis considers only the sensitivity of the mooring system life cycle cost to various wire rope replacement periods, the anchor size has not been increased although it will add an increment of cost.

Table 2 Environmental Conditions

	Operational	Extreme
Maximum wave height	36.2 ft	64.6 ft
Significant wave height	20.1 ft	35.9 ft
Period of maximum energy	10.3 sec	13.1 sec
Wind speed	46.5 kn	85.0 kn
Surface current	1.8 kn	2.4 kn

Note: Current, wind, and waves are colinear in their action on the moored barge.

Derivation of Cost Figures

Life cycle cost figures were derived for each of the three mooring system elements (seafloor foundation, platform foundation and connecting line). We considered costs associated with construction, initial deployment, and IM&R. All costs are in 1981 dollars. We did not consider possible increased costs for: inspection during manufacture; mooring instrumentation (e.g., real-time tension-measuring devices); required increased anchor size; an on-board monitoring computer; possible additional IM&R; and initial/periodic proof loading (using deck winches or tuggers, not tugs). Such costs would have to be considered as designs are finalized, but a cost analysis is beyond the scope of this paper.

In order to provide a perspective from which to view the costs of our example mooring system, we introduced the estimated costs from the Rosenblatt and Lockheed studies (1,2).

In this comparative approach, it was necessary to form a costing method which was common to Rosenblatt, Lockheed, and our example case. We chose to use the Rosenblatt cost method because it appeared sufficiently comprehensive for our purposes and was readily applied to the other cases. The Rosenblatt method is one using manual calculations. (The Lockheed method appears quite similar to that of Rosenblatt and has been programmed on a computer.)

The Rosenblatt method is based upon the following points:

- Mooring system costs are determined in terms of average annual costs and present value.
- The assumed interest rate - the cost of money - is 9 percent.
- Scrapping and resale costs are neglected.
- The replacement of galvanized wire rope is anticipated for set intervals (e.g., 8 years).

- o A 12.5-percent contingency is applied to the deployment cost estimate to allow for

  - possible loss of favorable weather window with resulting downtime during deployment and/or
  - possible higher equipment transportation costs.

- o Winches, anchors, and seafloor chain are expected to have a 30 year life.

- o The galvanized wire rope is

  - given a visual inspection of its upper segment every 6 months,
  - replaced at set intervals (e.g., 8 years), and
  - given a visual inspection of its lower segments every 4 years, using an RCV.

- o Inflation is not considered.

In our use of the Rosenblatt method we assumed a 10-percent annual inflation up to 1981, in order to cost all three studies in 1981 dollars. Further consideration of inflation was not deemed useful because the purpose of the present exercise is to obtain comparative rather than absolute cost values.

The Lockheed costing method differed slightly from the Rosenblatt approach in that

- o scrapping and disposal costs are considered,
- o local tax and marine insurance are considered,
- o seven-percent inflation is taken into account, and
- o a 10 year life is assumed for the wire rope.

Lockheed's method resulted in a life cycle cost of $44,885,000 for its 8-leg moored barge; using the Rosenblatt method, we derived a cost of $40,072,000.

For our own example system, we calculated life cycle costs for four different cases. In each case, everything was kept constant except wire rope life. We did the calculations for wire rope lives of 2, 4, 6, and 10 years. The results of all of the above calculations are presented in table 3.

We can readily conclude that decreased wire rope life is to be expected in light of recent findings. Such a decrease is noted expressly in the DnV study (10), which concluded: "The experience from short term application of wires in seawater indicates that they are severely exposed to corrosion. The lubricant is frequently washed out and rapid corrosion takes place. If the wires are properly galvanized, this may prolong the life to some degree. Experiences from components other than wires indicate that galvanizing is not adequate for long term protection in seawater. Lifetimes [of wire rope] up to 8 years are not realistic."

We can also conclude that a drastic decrease in wire rope life - such as from 10 years to 2 years - could nearly double the OTEC plant mooring system life cycle costs.

Table 3
Comparative Life Cycle Costs for
OTEC Mooring Systems

	CONSTRUCTION						
	Seafloor Foundation	Platform Foundation	Connect. Line	DEPLOYMENT	CABLE REPLACEMENTS	OTHER MAINTENANCE	LIFE CYCLE COST
M. Rosenblatt and Son							
Alt A (8-yr wire rope)	$888K	$12,201K	$19,021K	$3,193K	$ 7,973K	$3,073K	$46,349K
Alt B (30-yr wire rope)	930	12,242	22,351	3,234	0	3,618	42,375
Lockheed							
MAL 10-yr. wire rope)	3,655	13,480	13,005	2,735	3,599	3,380	40,072
OE8 Example							
10-yr. wire rope	930	12,242	17,454	3,234	5,435	3,618	42,913
6- "	"	"	"	"	11,686	"	49,164
4 "	"	"	"	"	20,039	"	57,517
2 "	"	"	"	"	43,837	"	81,315

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