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**PRELIMINARY DESIGNS FOR OTEC STATIONKEEPING SUBSYSTEMS
(SKSS)**

Summary Report

February 15, 1980

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Work Performed Under Contract No. EG-77-A-29-1078

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PRELIMINARY DESIGNS FOR OTEC
STATIONKEEPING SUBSYSTEMS (SKSS)
SUMMARY REPORT

LMSC-D677804

15 February 1980

Prepared for
NOAA, OFFICE OF OCEAN ENGINEERING
by
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FOREWORD

Lockheed Ocean Systems is performing the Preliminary Design for OTEC Stationkeeping Subsystems (SKSS) study contract NA-79-SAC-00635 for NOAA, Office of Ocean Engineering, in support of the Department of Energy, Ocean Thermal Energy Conversion (OTEC) program. Participating with Lockheed are IMODCO on design and analysis of mooring systems for the spar, Simplex Wire and Cable Company on SKSS interface with the Electrical Transmission System riser cable, and Eager & Associates on reliability assessment. The results of this study are reported as follows:

- o Task I, Design Requirements, LMSC-D673832
- o Task II, Conceptual Design, LMSC-D676379
- o Tasks III, V and VI, Preliminary Design, LMSC-D678771
- o Task IV, Development and Testing Recommendations, LMSC-D677783

This report presents a concise summary of the SKSS designs and technological accomplishments achieved in this study. The reader is referred to the above reports as the primary source of information contained herein.

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Section 1

INTRODUCTION

Lockheed Ocean Systems and IMODCO have completed a preliminary design study for OTEC Stationkeeping Subsystem (SKSS) for the pilot plants under contract to NOAA, Office of Ocean Engineering, in support of the Department of Energy, OTEC solar energy program. The results of this study are contained in the series of referenced reports. This summary report presents a condensation of the designs as developed from requirements and concept selection to preliminary design.

The study consists of the following six tasks:

1. Design Requirements. Establish design environmental conditions and criteria. Develop methodology to both assess SKSS reliability and performance, and minimize life cycle costs.
2. Conceptual Design. Develop at least two SKSS conceptual designs for both barge and spar platform (eight in all). Consider commercial plant SKSS, verify feasibility, define problem areas, estimate life cycle cost. Develop deployment, operation and maintenance scenarios. Recommend an SKSS concept for each platform.
3. Preliminary Design. Prepare preliminary designs for two SKSS concepts selected by NOAA/DOE. Optimize the designs, provide deployment and retrieval procedures, support requirements, evaluate reliability and performance. Assess effects of watch circle and water depth variation.
4. Development and Testing Recommendations. Recommend programs required to confirm design assumptions and performance predictions, including material and component development, and soils investigation. Estimate cost and schedule required to perform these programs.
5. Cost-Time Analysis. Develop a detailed cost and schedule for the acquisition, transportation, deployment, inspection, maintenance, spares, replacement and salvage for the SKSS designs.

6. Commercial Plant SKSS Recommendations. Assess applicability of designs to Commercial Plant SKSS. Recommend development program and at-sea tests as required with estimate of cost and schedule.

The design requirements, summarized in Section 2, include environment, design sea states, performance requirements and design criteria. Conceptual designs for the barge and spar are presented in Section 3, followed by concepts for electrical risers; reliability and risk assessment, cost, evaluation and ranking complete the section.

Section 4 contains the preliminary designs of the selected multiple anchor leg with active tensioning SKSS for the barge, followed by the tension anchor leg SKSS for the spar. An engineering description of each design is followed by prediction of loads and response in a seaway, installation procedures, and sensitivity to requirements. Capital and life cycle costs, as well as schedule are given for both designs in Section 4.3.

Finally, development and testing recommendations are summarized in Section 5, and conclusions and recommendations are presented in Section 6.

Section 2

REQUIREMENTS

2.1 ENVIRONMENTAL CONDITIONS

Environmental features of the Punta Tuna, Puerto Rico, site which are relevant to mooring design are presented in this section. A brief description of bathymetry is followed by a presentation of current, wind, and wave conditions. These data are synthesized in the Design Sea States and a weather window is identified. A compilation of results is presented in Table 2-1.

2.1.1 Site Geology and Bathymetry

The site is located over the steep island slope on the southeast coast of Puerto Rico at Punta Tuna (Fig. 2-1). Average bottom slope is 15 deg. Seafloor surface quality is variable and includes calcareous ooze ranging in grain size from clay-like silt to silty mud underlain by dense sand, the latter indicative of a high-strength bottom. Subsurface soils data are not available.

2.1.2 Current

Data on current for the site are incomplete, particularly with regard to surface speed, speed and direction variation with depth, and seasonal variation. Surface current is generally easterly or westerly following seafloor contour and daily tides. Measured flow direction to a depth of 200 m is either 65 ± 35 deg, or 265 ± 25 deg, with equal probability of 0.5, and 240 ± 15 deg below 200 m. Local wind-driven surface current components are in the direction of and normal to wind direction.

Surface current speed observations range from 0.3 to 0.75 knot compared with predicted geostrophic current of 0.82 knot and 0.39 knot tidal current,

Table 2-1 SUMMARY OF ENVIRONMENTAL CONDITIONS, PUNTA TUNA

Property	Condition
Climate	Marine Tropical
Latitude	17° 57' N
Longitude	65° 52' W
Approximate Depth (ft)	4,000 ^(a)
Distance to Shore (miles)	3
Distance along Shore (miles)	± 5
Return Period of Design Operational Sea State (years)	3
Return Period of Design Extreme Sea State (years)	100
Surface Current (knots)	1.8 to 2.4
Bottom Quality	Silt, Clay, Mud, underlain by dense sand
Bottom Slope (deg)	10 to 18
Operational Sea State:	
Maximum Wave Height (ft)	36.2
Significant Wave Height (ft)	20.1
Period of Maximum Energy (sec)	10.3
Wind (knots)	46.5
Surface Current (knots)	1.8
Seafloor Current (knots)	0.18
Current Profile	(b)
Astronomical Tide (Diurnal Range) (ft)	1.0
Astronomical Tide (Annual Max. Range) (ft)	1.8
Extreme Sea State:	
Maximum Wave Height (ft)	64.6
Significant Wave Height (ft)	35.9
Period of Maximum Energy (sec)	13.1
Wind (knots)	85.0
Surface Current (knots)	2.4
Seafloor Current (knots)	0.24
Current Profile	(b)
Astronomical Tide-Storm Surge (ft)	5.5

(a) Depth for the tension anchor leg is 3281 ft.

(b) See Fig. 2-2.

Fig. 2-1 Bathymetric Chart Showing Steep Slope at Punta Tuna

Fig. 2-2 Current Profile for Modular Experiment Plant Site in Puerto Rico (Ref. 2-2)

yielding 1.21 knots combined. The decrease of observed current with depth is bound by the "extreme" current profile (Fig. 2-2) with $V_s = 0.3$ knot. An average value of observations is 0.6 knot. The surface current for the operational sea state, including geostrophic, tidal and wind driven current, is given by

$$V_{MAX} = 1.8 \text{ knots}$$

$$\Theta_R = 16 \text{ deg}$$

The surface current for the Extreme Sea State is

$$V_{MAX} = 2.4 \text{ knots}$$

$$\Theta_R = 23.8 \text{ deg}$$

where Θ_R is the angle of current to the right of the wind direction.

2.1.3 Wind

Synoptic meteorological observations provide data on wind frequency, magnitude, and direction for the general area in which Punta Tuna is situated. Wind criteria for Service and Operational Sea States are derived from ship observations, while hurricane predictions provide criteria for the Extreme Sea State. Wind direction is easterly. Due to the counter clockwise wind path in a hurricane, the wind direction for a hurricane passing north or east of the site is westerly.

Wind speed is derived as a function of significant wave height based on the sea state spectra. Wind speed for all Sea States is given by the following least squares fit to this data,

$$U = 10.96 \ln (23.27 * T)$$

where

U = wind speed, knots

T = return period of storm, years

2.1.4 Waves

The seaway is characterized by significant wave height, period, and direction. Wave height is expressed as a function of return period or recurrence interval based on meteorological observations of storms and on hurricane predictions. Wave period is expressed as a function of wave height for storms and hurricanes. Wave direction is characterized by probability of exceedance based on observations of storms and hurricane tracks.

A least-squares fit to joint cumulative probability distribution of observations and hurricane hindcasts yields the following expressions for significant wave height and period for storms not exceeding 21 ft:

$$H_{1/3} = 4.51 \ln (27.83 \times T)$$

$$T_o = \text{EXP} (0.507 \times \ln (5 \times H_{1/3}))$$

where

$H_{1/3}$ = significant wave height, ft

T = return period, years

T_o = spectral modal period, sec

Wave period for hurricane conditions is derived by fitting the Bretschneider hindcasts for the 50- and 100-year most probable hurricanes. The following expression is assumed to be applicable for heights in excess of 21 ft:

$$T_o = \exp (0.412 \times \ln (14.51 \times H_{1/3}))$$

The mean direction from which sea and swell progress is 55 deg, or northeast. Wave direction in the hurricane condition is assumed to be equal to the wind direction.

2.2 DESIGN SEA STATES

Environmental factors for design include three categories of Sea State: Service, Operational, and Extreme. The Service Sea States are the set of wind, wave, current and other oceanic factors that contribute to cyclic loading of the mooring system.

The Operational Sea State is the highest wind, wave, and current condition for which the platform must remain operational and constrained within the required watch circle. The return for this sea state is assigned a value of 3 years. The conditions for this sea state, derived from the preceeding equations, are summarized in Table 2-1.

The Extreme Sea State is the set of highest wind, wave and current conditions for which station must be maintained with no grounding of the CWP. The design return period is assigned a value of 100 years. This sea state, representative of a tropical hurricane, is summarized in Table 2-1.

Weather windows are the periods of relatively low levels of wind, wave and current at the operational site. These periods are associated with critical operations including deployment, maintenance, and repair. Tropical cyclones are most frequent in August and September, less frequent in July, October, and November, and absent in the period December through June. The latter period is therefore identified as the general weather window of 7 months duration. Other conditions such as available hours of daylight and level of precipitation are also considered in selection of the weather window for specific operations. The following periods have the lowest frequency of occurrence of waves 5 ft and greater throughout the year:

<u>Duration (Months)</u>	<u>Weather Window</u>
1	April
2	March - April
3	March - May
4	February - May
5	January - May
6	December - May

2.3 STATIONKEEPING SUBSYSTEM REQUIREMENTS

SKSS requirements are presented in this section and include performance requirements, interface requirements, and criteria for design.

2.3.1 Performance Requirements

The system requirements are significantly influenced by the mission defined for the OTEC Pilot Plant. The plant is a stationary 40-MW(e) power plant to be moored off Punta Tuna, Puerto Rico, for the purpose of transmitting electrical power via a submarine cable to the Puerto Rican grid for a service period of thirty years. The system is required to constrain the plant within a watch circle of 400 ft radius in all sea states up to and including the Operational Sea State. The system is required to constrain the platform to prevent cold water pipe (CWP) grounding and to survive the Extreme Sea State.

2.3.2 Interface Requirements

The influence of the OTEC ocean systems and electrical transmission system on the SKSS requirements is examined in terms of the functional and physical interfaces which exist among these systems. In particular, the platform configuration, cold water pipe, and electrical transmission riser cable lead to system design requirements.

Mooring systems are required for positioning two different ocean platforms - the ship type and spar. The characteristics of the barge and spar platforms are given in Table 2-2 and Figs. 2-3 and 2-4.

Table 2-2 BARGE AND SPAR CHARACTERISTICS

Characteristics	Barge	Spar
LOA (ft)	381.5	-
LWL (ft)	378	35
Beam - Max (ft)	121	200
Draft (ft) (Excluding Discharge Pipes)	65	215
Depth (ft)	89	290
Displacement (1t)	67,901	54,300
CWP Diameter (ft)	30	30
CWP Length (ft)	2,935	2,785
Wind Area (Beam) (ft ²)	13,434	4,425
Wind Area (Frontal) (ft ²)	7,460	4,425
Current Area (Beam) (ft ²)	112,820	124,030
Current Area (Frontal) (ft ²)	95,915	124,030
Length/Beam	3.15	1.0

Interface considerations include the following: space to lead-in lines; force and moments on hull and spar; material compatibility between mooring lines, winches, and fittings; the remaining ocean systems and power system.

The mooring system is designed to maximize the modular experiment plant operability,

$$\text{MAX [OPERABILITY]} = \text{MAX} \left[\frac{\text{OPERATING TIME ON STATION}}{\text{TOTAL TIME ON STATION}} \right]$$

wherein operation is defined as the transmission of electrical power via the riser cable and submarine cable to the grid on Puerto Rico. Cable operation is not required beyond the Operational Sea State. However, criteria for suspension of operation which are influenced by mooring system performance characteristics include maximum tolerable amplitudes of:

- o Stress in the riser cable
- o Stress in the mooring lines

Fig. 2-3 Barge Projected Areas and Drag Coefficients

Fig. 2-4 Spar Projected Areas and Drag Coefficients

- o Off-station excursions
- o Platform Seakeeping (motions, heading, deck wetness, freeboard)
- o Stress in CWP
- o Cable-anchor leg relative excursions

The watch circle must be consistent with the riser cable system layout in that physical contact of the cable with the platform, mooring system, or the CWP must be avoided to preclude physical damage to the cable. The greatest consideration in limiting rotation of the cable end may be the physical interference of multiple riser cables with the power plant and each other. A working limit of plant yaw rotation of less than ± 90 deg is necessary to avoid physical interferences between cables, between cables and plant structures, and between riser cables and anchor legs.

The SKSS-CWP interface is particularly significant in the tension anchor leg concept wherein the wave response of the spar, dependent on pre-tension in the pipe, dictates pipe design loads. Clearance between the pipe and anchor leg is required for the multiple anchor leg concept.

2.4 CRITERIA FOR DESIGN

The standards used in the design of the stationkeeping system are the rules for building and classing offshore structures and other appropriate rules or guidelines now under development. The application of these standards along with appropriate safety factors for individual components leads to the criteria summarized in Table 2-3.

Table 2-3 SUMMARY OF SKSS DESIGN CRITERIA

Loading Criteria and Safety Factors

- o Anchor Pullout Safety Factor $\frac{\text{Wet Weight of Anchor}}{\text{Vertical Force Component}}$ (Des. Min.) = 2
- o Anchor Leg Safety Factor on Breaking Strength = 2-3
- o Horizontal Anchor Pull Angle - Tangent to 6 deg

Anchor Holding Power:

- o Nominal Operating - $\frac{\text{Anchor Holding Power}}{\text{Horiz. Force Comp. For } 1/3 \text{ Line Breaking Strength}} \geq 2$
- o Maximum Operating - $\frac{\text{Anchor Holding Power}}{\text{Horiz. Force Comp. for } 1/2 \text{ Line Breaking Strength}} = 2$
- o Survival Condition - Anchor slip permissible. Maximum excursion restricted to prevention of cold water pipe grounding (<3,000 ft, 75% of depth).

Mooring Bearings Design Safety Factor Without Destructive Yielding of Surface ≥ 2

Safety Factor for Synthetic Lines ≥ 5

Hawser Load (SPM Through Different Faileads - Max. of 2)
Number of Separated Mooring Lines $\geq 40\%$ Break. Str.

Hawser Load (Sin. Mrg Line W/Multiple Parts Thru 1 Fairlead)
Number of the Individual Parts of the Line $\geq 60\%$ Break. Str.

<u>Mooring System Stiffness</u>	<u>Maximum Tension/ Breaking Strength</u>	<u>Excursion, % Depth</u>
Very Nominal	< 1/3	3
Nominal	1/3	5 to 10
Maximum	1/3 to 1/2	10 to 20
Unrestricted (Survival)	< 1.0	< 75

Pretension: The initial tension in all lines at zero excursion such that 1/3 the rated breaking strength of the mooring line is reached at 5 to 10 percent of depth excursion

Safety Factor: The maximum factor of safety in design life of components with loads based on maximum loading in Extreme Sea State

Allowable Structural Stress Levels

- o Gravity and Mooring Loading:
 - 60% of yield strength for tensile stresses

Table 2-3 (Cont.)

- 60% of either the local buckling or yield strength, whichever is less, for bending stresses
- 57% of either the buckling or yield strength, whichever is less, for compressive stresses
- 40% of tensile yield strength for shear stresses
- o Combined Loadings:
 - 80% of yield strength for tensile stresses
 - 80% of either the buckling or yield strength, whichever is less, for bending stresses
 - 75% of either the buckling or yield strength, whichever is less, for compressive stresses
 - 53% of tensile yield strength for shear stresses
- o Compressive Stresses from Combined Axial and Bending Loadings

$$f_a/F_a + f_b/F_b \leq 1.0$$

f_a = Computed axial compressive stress

f_b = computed compressive bending plus local stress

F_a = allowable axial compressive stress based on overall buckling strength, local buckling strength, or yield strength, whichever is the smallest

F_b = allowable bending compressive stress based on local buckling strength, or yield strength, whichever is the smallest

- o Column Buckling Stresses:

Elastic Buckling Stress

$$F_e = \pi^2 E / (KL/r)^2 \quad \text{where } KL/r \geq \sqrt{2\pi^2 E / F_y}$$

F_e = elastic buckling stress

F_y = yield stress

E = modulus of elasticity

Table 2-3 (Cont.)

- L = column length
 r = least radius of gyration
 K = an effective length factor to be determined as per the latest AISC code (dimensionless)

- o Critical Buckling Stress of a Column:

$$F_c = F_y - (F_y^2 / 4 \pi^2 E) (KL/r)^2$$

where $KL/r < \sqrt{2 \pi^2 E / F_y}$

Pile and Pile Foundation

- o $\frac{\text{Ultimate Soil Capacities}}{\text{Allowable Soil Capacities}} = 2$
 o Ultimate Bearing Capacity:

$$Q_d = Q_t + Q_p = fA_s + qA_p$$

- Q_t = skin friction resistance (lb)
 Q_p = total end bearing (lb)
 f = unit skin friction capacity (lb/ft²)
 A_s = side surface area of pile (ft²)
 q = unit end bearing capacity (lb/ft²)
 A_p = gross end area of pile (ft²)
 qA_p = capacity of internal plug (lb)

- o Load to Foundation Safety Factor = 2
 o Maximum Pile Deflection $\leq 1/10$ Pile Diameter

Break up Block

Section 3

CONCEPTUAL DESIGNS

SKSS conceptual designs developed for evaluation and selection for preliminary design are presented in this section first for the barge followed by those for the spar. A cost analysis including cost estimates, life cycle cost scenarios leading to expected value of cost, and cost equivalence of operational failures are presented. Finally, an evaluation of the concepts is presented, including assessment of performance and rankings based on both risk versus cost and on technology development. These concepts are sized based on estimated platform environmental loads which were subsequently increased in part as a result of revision to the Design Sea States (Ref. 2, Sec. 3).

The conceptual designs studied include six barge mooring configurations of single and multiple anchor legs and three spar mooring configurations of multiple, tension anchor leg and monopod. Figure 3-1 illustrates the ten mooring configurations for the barge and spar.

3.1 BARGE MOORING CONCEPTS

3.1.1 Multiple Anchor Leg (MAL)

The MAL mooring system consists of a radial, catenary pattern of ten wire rope and chain combination anchor legs with two drag-embedment anchors per leg. The lines run through fairleads just below the waterline and up to the main deck structure (see Fig. 3-2). The radial pattern of the mooring legs constrains platform rotation. Watch circle radius is 8.8 percent of the depth for the Operational Sea State and 13.0 percent of the depth for the Extreme Sea State. Each 8 100-ft leg consists of 4 500 ft of at least 3 5/8-in.-diameter chain and 3,600 ft of 4 1/2-in.-diameter wire rope in a catenary profile. Sufficient material is added to the chain for life cycle wear and abrasion. This length of chain facilitates wire rope change-outs

Fig. 3-1 Conceptual Design Study Mooring Configurations

Fig. 3-2 MAL Mooring System

over the power plant life cycle. Chain weight allows the use of 20,000-lb drag-embedment anchors. Figure 3-2 shows the arrangement of the MAL. Static performance is summarized in Table 3-1.

3.1.2 Multiple Anchor Leg - Single Point Moor

This concept consists of a cluster of seven anchor legs between a single deadweight anchor and a buoy which supports the weight of the wire ropes and line tension. The barge is connected to the buoy by either hawsers or a yoke assembly. The specific components of the system are a deadweight anchor weighing 15.7 million lb (dry), seven 4 1/2-in.-diameter wire ropes, a 30 ft-diameter, 200-ft-long spar buoy weighing approximately 750,000 pounds, and a minimum of two swivels, one at the anchor and the other at the buoy. Direct-lift methods do not presently exist for deployment of the large deadweight anchor since the load is beyond the capacity of existing heavy lift equipment. The deadweight anchor may be implanted by pouring fresh concrete in-situ or by free-fall emplacement. Figure 3-3 shows the arrangement of the MAL-SPM. The performance is summarized in Table 3-2. Anchor retrieval following plant service life is not feasible.

Table 3-1 MAL PERFORMANCE CHARACTERISTICS

Item	3-Year Storm	100-Year Storm
Horizontal Force on Barge (lb)	729,529	1,202,843
Anchor Leg Tension (lb)	624,200	790,500
Chain Safety Factor	3.06	2.42
Wire Rope Safety Factor	2.96	2.34
Watch Circle Radius (ft)	350	530
Watch Circle/Depth (percent)	8.8	13.3

Fig. 3-3 MAL - SPM

3.1.3 MAL-Turret

The conceptual design of the anchor legs for the MAL-Turret is identical to the MAL and consists of a radial, catenary pattern of ten wire rope and chain combination anchor legs with drag embedment anchors. In contrast to the MAL, the anchor legs lead through fairleads attached to the CWP below the hull and up to the turret in the barge structure. The turret head is secured to the end of the cold water pipe. The conceptual design of the mooring turret is shown in Fig. 3-4.

Table 3-2 MAL-SINGLE POINT MOOR PERFORMANCE CHARACTERISTICS

Item	3-Year Storm	100-Year Storm
Horizontal Force (lb)	338,202	585,070
Vertical Force (lb)	3,382,000	5,861,700
Buoy Inclination (deg)	6	6
Anchor Leg Tension (lb)	3,398,800	5,890,800
Anchor Leg Safety Factor	3.81	2.20
Deadweight - Anchor Weight Wet (lb)	9,000,000	9,000,000
Deadweight - Dry (lb)	15,697,700	15,697,700
Deadweight Safety Factor	2.66	1.54
Watch Circle Radius (ft)	400	400

Fig. 3-4 MAL-Turret Concept

3.1.4 MAL - Active Tensioning

The anchor legs and anchors for the MAL-active tensioning are also identical to those of the MAL. The lines run through fairleads just below the waterline and up to the main deck structure. At this point, hydraulic windlasses or winches respond to take-up, hold or slack control signals depending on yaw angle, anchor leg tensions, platform motions, etc. The active tensioning system provides a control system for adjustment and monitoring of line tensions, excursions, yaw, and restoring forces during normal and extreme conditions.

3.1.5 Single Anchor Leg - Single Point Moor (SAL - SPM)

This mooring concept, wherein a single anchor leg leads from a deadweight anchor to a mooring buoy, is necessarily a tension anchor leg system to satisfy the watch circle requirement. The single leg must react to 5.9-million-lb tension in the extreme sea state of 100-year return period. Wire rope with breaking strength of about half this amount is available. An anchor leg consisting of hollow cylindrical links would be difficult to maintain, particularly in the area of the pin joints and requires development. A single anchor leg chain with the requisite breaking strength is excessively heavy, lacks redundancy, requires a massive buoy, and is costly. The system is therefore not feasible within present technology.

An alternate single point concept employs a yoke which attaches the vessel to the mooring buoy. The mooring buoy is a buoyant structure which is connected to a gravity mooring base on the seabed by a wire rope anchor leg and universal joints which allow the buoy to rotate in any direction. The mooring yoke is attached at the top by means of a tri-axial universal joint which accommodates all movements of the yoke. The yoke is connected to the OTEC vessel's structural extensions by means of pivot joints, which permit the vessel to pitch relative to the yoke, as seen in Fig. 3-5.

Fig. 3-5 Single Anchor Leg-Single Point Moor

The mooring buoy includes a large buoyancy chamber near the upper end of the buoy and a ballast chamber at the bottom. The overall net buoyancy of the system is 250 kips. The buoy structure is an all-welded steel structure, with concrete ballast. The moment provided by the buoyancy provides a restoring force in response to the vessel displacements caused by environmental forces.

A tri-axial swivel universal joint is mounted at the top of the buoy. The mooring yoke is a fabricated tubular steel structure, configured as an A-frame. It is attached at its apex to the tri-axial universal joint and at its base to two pivot joints fitted on the bow of the vessel. The anchor leg assembly connects the mooring buoy to the mooring base through which all loads are transferred. The anchor leg consists of 4 1/2 in. diameter galvanized wire rope and a section of joining shackles. The wire rope and sockets are covered with a polyethylene jacket which is 1/4 in. thick.

3.1.6 MAL - Rotary

The rotary system consists of carriages which run on a circular rail around the CWP or on the barge. Anchor legs attached to these carriages are spaced from each other by chains which connect the carriages together. The ship rotates relative to the anchor legs. The electric transmission riser cable is also supported by another carriage which rides on the circular rail. An electric slipring allows the ship to rotate relative to the riser. The swivel is pressure resistant, as ingress of small amounts of water will eventually contaminate the oil or gas insulation. In addition, this concept requires electrical contact surfaces around the CWP, a termination difficult to seal and insulate. Finally, the necessary mechanical cable terminations require space and clearance unavailable in the rotary concept. The interface of the riser cable with the rotary system underwater renders this concept unfeasible, and it is not considered further in concept evaluation and ranking.

3.2 SPAR MOORING CONCEPTS

3.2.1 Multiple Anchor Leg

The multiple anchor leg mooring system for the spar consists of four catenary anchor legs attached to the core of the spar as shown in Fig. 3-6 (Ref. 3).

The anchor leg has three segments joined together in series. The leading segment, attached to the Spar, is 100 ft of 4-in. diameter chain. The chain is of U-3 quality with a breaking strength of 1,632 kips. The second segment is 5,000 ft of 4 1/2 in. diameter galvanized wire rope. The wire rope has a breaking strength of 1,850 kips. A protective coating of polyethylene, 1/4 in. thick, is applied to the wire rope. The final segment is 5,900 ft of 4 in. diameter chain with two drag embedment anchors attached near the end. A chain swivel is included in the mooring leg.

The anchoring system for the multiple anchor leg consists of two anchors arranged in series. The total holding power from the two anchors is 1,750 kips. Separating the two anchors is approximately 90 ft of chain. Four chain attachment assemblies are attached to the outer shell of the power plant core. The hawse pipes are placed near the top of the core, between the evaporators and condensers.

3.2.2 Tension Anchor Leg (TAL)

The spar vessel, shown in Fig. 3-7, consists of a main body containing the power plant, and eight vertical discharge pipes containing the four evaporator modules and the four condenser modules. A hinge under the spar connects it to the top of the CWP. Net positive buoyancy in the spar maintains a constant tension in the hinge in calm water.

Fig. 3-7 Tension Anchor Leg Mooring Elevation View

The CWP sections consist of a steel cylindrical shell with vertical and transverse stiffeners. The shell is 30 ft in diameter with external stiffeners that increase the effective diameter to 32.4 ft. The lowest section of the CWP extends down to the mooring base universal joint. The cold water inlet is located within this section of pipe. The universal joint at the base allows angular motion between the CWP and the base, while transmitting the tension between them. The mooring base consists of a steel shell and frame, filled in-situ with cement grout. Mooring loads are resisted by the weight of the base and by friction between the base and soil.

3.2.3 Tension Anchor Leg-Monopod

The TAL-Monopod is similar to the TAL previously described except for the absence of joints in the CWP. The spar and CWP act as a rigid body between the surface and the base universal joint. The CWP is designed to carry large bending moments.

3.3 ELECTRICAL TRANSMISSION CABLE CONCEPTS

From the standpoint of the power cable system, the mooring systems can be divided into three major groups: the TAL, SAL, and MAL systems. The physical deployment characteristics of the electric transmission system are basically the same for each particular mooring system within any one group. It is important to note that four cables are necessary for the electrical transmission system. A matrix of the possible combinations of specific mooring systems and specific cable systems is shown in Table 3-3. As noted in Table 3-3, some of these designs require an electrical swivel to parallel the mechanical swivel. Such a device is untried, even at the power level of 10 MW.

An estimate of riser cable system costs based on the stand-off buoy system is approximately \$10 million, decreasing to 8.3 million as the watch circle decreases from 30 percent of water depth to 10 percent. Catenary direct descent riser cost is \$6.9 million and the vertical descent cost is

Table 3-3 ELECTRICAL RISER CONCEPTS

	Vertical Descent	Catenary Direct Descent	Stand-Off Buoy	Comments
SAL Single Point Moor	Probable	Must Clear CWP	No	Needs electric swivel surface & subsurface
MAL	No	Possible	Probable	
MAL Active Tensioning	No	Possible	Probable	Must allow for changing configuration of mooring
MAL Turret	No	Possible	Probable	Needs electrical swivel
MAL Rotary	No	Possible	Probable	Needs underwater electric swivel extremely difficult to interface cable hardware with rotary
MAL Single Point	Possible	Must Clear CWP	No	Needs electrical swivel
TAL	Probable	Possible	Possible	Attachment to CWP must be developed
TAL Monopod	Probable	Possible	Possible	

\$8.3 million. Neither of the latter two riser systems is easily adaptable to watch circles greater than 10 percent.

All of the MAL systems, with the exception of the MAL single point moor, are basically similar from the standpoint of the cable system. The MAL allows more motion of the OTEC plant than do the TALs, and the MALs do not allow rotation of the CWP as do the SALs. This combination of mooring characteristics makes the catenary direct descent or the stand-off buoy system the most viable. The stand-off buoy system allows the greatest potential

watch circle and the greatest flexibility for tailoring the system to particular locations.

The primary advantage of the catenary direct descent system is simplicity. Hardware and installation costs are minimized. However, the extent of plant watch circle which can be accommodated is substantially less than the stand-off buoy system. Design flexibility to accommodate varying bottom conditions or to detune the system is also reduced. The small watch circles and negligible base movements allowed by the TAL allow the possibility of a direct descent riser cable.

Two different methods of bringing the cable up to the CWP are considered for the TAL and monopod designs. In a TAL mooring, the riser cable is attached to the base of the CWP. From here it either passes through a stand-off buoy, then reaching bottom, or hangs in a catenary to the ocean bottom. The effects of abrasion on the cable behavior require investigation. In the case of the monopod, the supporting structure allows the cable to be attached down to the platform anchor. However, a catenary attachment on the order of 100 ft from the sea floor is necessary to absorb plant motions. An extra length of free cable to allow lift off is required as with the longer catenary. The bottom end, in this case, requires a bend limiting anchor.

The riser cable joins the CWP through a bend restricting bell housing and passes along the CWP through spaced supports. These supports provide horizontal control to avoid chafing against the CWP, but vertical support of the cable is not possible within the SOA. Static and dynamic tensions, electric heating and twisting torque in the cable create complex strains that make mating of the cable and CWP in the vertical direction extremely difficult.

The riser cable is fixed to a point on the CWP below the universal joint. This allows the suspension load to be taken off the cable, permitting flexibility for passage around the universal.

3.4 RELATIVE RELIABILITY AND RISK ASSESSMENT

The eight Stationkeeping Subsystem concepts are evaluated in terms of relative risk and criticality of failure. The ship hull mooring concepts, ranked in order of increasing risk and criticality of failure, are:

- o Multiple-anchor-leg/multiple-point moor, turret or rotary
- o Multiple-anchor-leg/multiple-point moor
- o Multiple-anchor-leg/multiple-point moor, active tensioning
- o Multiple-anchor-leg/single-point moor
- o Single-anchor-leg/single-point moor

For the spar platform the ranked concepts are:

- o Multiple-anchor-leg/multiple-point moor
- o Tension-anchor-leg moor or tension-anchor-leg-monopod moor

Discrimination cannot be made either between the turret and rotary versions of the barge moors or between the tension-anchor-leg and monopod versions of the spar moors at the concept level of detail. The catenary single-anchor-leg/single-point moor does not provide acceptable reliability for OTEC use because it is susceptible to entanglement in its slack condition.

Although the OTEC SKSS is subject to exceptionally severe conditions, acceptable reliability can be achieved. A highly disciplined development program is required, carefully utilizing all major risk-reduction opportunities.

The following definitions are used:

- o The reliability of the mooring system is the probability that the mooring system will perform its function of maintaining station for the specified design life of 30 years.
- o Net risk factor for a specific mooring system concept is an inverse measure of the relative reliability predicted for that concept. Values are based upon the concept's failure modes, their associated risk conditions, and the assumption that all inherent opportunities for reducing risk will be exploited to the maximum practicable extent.

- o The criticality factor assigned to a specific failure mode is a relative measure of the adverse impact upon the OTEC program resulting from that failure mode.

The relative risk and failure criticality factors for each concept are derived from concept level failure modes analyses, from readily available data on deep water moorings, and from other deep ocean facilities. The risk and criticality factors presented are suitable for selecting concepts for preliminary design. These factors also provide a suitable basis for setting initial priorities for the planning, data acquisition, analysis, and design and development efforts. Through these efforts, progressive refinement of the risk and criticality factors are obtainable.

The risk conditions, risk reduction opportunities, and criticality determinants for each of the basic concepts are listed on the ordinate, as shown in Tables 3-4 and 3-5. Those risk conditions, risk reduction opportunities, and criticality determinants that could be effective are identified under each failure mode. High numbers of identified risk conditions or high probability of failure produces an assigned risk factor of 10 for that failure mode. The inherent and available risk reduction opportunities are reviewed to determine the degree to which they could be used to compensate for the risk conditions. The risk reduction factors are deduced, listed under that failure mode, and subtracted from the risk factor to derive the net risk factor. Criticality factors are determined and listed under each failure mode. Finally, the risk-criticality factor is calculated for each failure mode by multiplying the net risk factor by the criticality factor. The risk-criticality factors are then summed across the failure modes to achieve a ranking of the concept on a risk-criticality basis. The lower the number, the more favorable the concept.

3.5 COST ANALYSIS

This section treats the capital, operating, and overall life cycle cost (LCC) of the SKSS concepts.

Table 3-4 RISK AND CRITICALITY ASSESSMENT MATRIX FOR MAL-MPM (BARGE)

FAILURE MODES	ETC DAM FLR	ETC DAM PIPE	ETC DAM LEG	SLIP RING FAIL	ANCH PULL OUT	LEG DAM MULT	LEG DAM PIPE	MOOR CONN DAM	BUOY DAM MULT	SHIP CONN DAM	TOTAL
RISK CONDITIONS											
Pretension					x	x		x		x	
Dynamic Tension	x		x		x	x		x		x	
Relative Motion	x	x	x		x	x	x	x		x	
Unproven Compon	x		x								
Mult Interface						x		x		x	
Complex Interact	x				x	x		x		x	
Complex Environ					x	x		x			
Complex Install	x	x	x		x	x	x	x			
RISK FACTOR	10	5	5		10	10	5	10		10	
RISK REDUCTION OPPORTUNITY											
Environ Measure	x	x	x		x	x	x	x		x	
Rep Analysis	x	x	x		x	x	x	x		x	
Load Mitigation											
Self Load "	x	x	x		x	x	x	x		x	
Redundancy					x	x		x		x	
Safety Factor					x	x		x		x	
Rep Testing					x	x		x		x	
Detect-Correct					x	x		x		x	
Install Simplif	x	x	x		x	x	x	x		x	
RISK REDUCTION FACTOR	7	5	5		9	8	5	6		9	
NET RISK FACTOR	3	0	0		1	2	0	4		1	
CRITICALITY DETERMINANTS											
Personnel Injury					x	x		x		x	
Downtime	x	x	x		x	x	x	x		x	
Recovery Cost	x	x	x		x	x	x	x		x	
CRITICALITY FACTOR	2	2	2		10	10	3	10		10	
RISK-CRITICALITY FACTOR	6	0	0		10	20	0	40			86

CONCEPT RISK-CRITICALITY FACTOR: 86 MAL-MPM
52 MAL-MPM-Turret or Rotary
104 MAL-MPM-Active Tensioning

Table 3-5 RISK AND CRITICALITY ASSESSMENT MATRIX FOR TAL (SPAR)

FAILURE MODES	ETC DAM FLR	ETC DAM PIPE	ETC DAM LEG	SLIP RING FAIL	ANCH PULL OUT	LEG DAM MULT	LEG DAM PIPE	MOOR CONN DAM	BUOY DAM MULT	SHIP CONN DAM	TOTAL
RISK CONDITIONS											
Pretension					x	x		x	x		
Dynamic Tension	x				x	x	x	x	x		
Relative Motion	x	x	x		x	x	x	x	x		
Unproven Compon	x				x				x		
Mult Interface											
Complex Interact					x	x	x	x	x		
Complex Environ					x	x			x		
Complex Install	x	x	x		x	x	x	x	x		
RISK FACTOR	10	5	5		10	10	10	10	10		
RISK REDUCTION OPPORTUNITY											
Environ Measure	x	x	x		x	x	x	x	x		
Rep Analysis	x	x	x		x	x	x	x	x		
Load Mitigation	x				x	x	x	x	x		
Self Load "	x	x	x		x	x	x	x	x		
Redundancy					x	x	x	x			
Safety Factor	x				x	x	x	x	x		
Rep Testing	x				x	x	x	x	x		
Detect-Correct						x	x	x			
Install Simplif	x	x	x		x	x	x	x	x		
RISK REDUCTION FACTOR	9	5	5		8	8	9	7	8		
NET RISK FACTOR	1	0	0		2	2	1	3	2		
CRITICALITY DETERMINANTS											
Personnel Injury					x	x	x	x	x		
Downtime	x	x	x		x	x	x	x	x		
Recovery Cost	x	x	x		x	x	x	x	x		
CRITICALITY FACTOR	2	2	2		10	10	10	10	10		
RISK-CRITICALITY FACTOR	2	0	0		20	20	10	30	20		102

CONCEPT RISK-CRITICALITY FACTOR: 102 TAL
 110 TAL Monopod
 82 MAL-MPM
 120 MAL-MPM-Active Tensioning

The capital costs of the SKSS concepts are summarized in Table 3-6. All estimates are in mid-1979 dollars, and include contingency, freight, storage, insurance, handling costs, and fee. As can be seen, the total capital costs of all but the TAL systems are quite similar ranging from just over \$22 to slightly over \$28 million; the costs of the TAL concepts are significantly lower. The TAL monopod concept, eliminating the requirement for a tension leg member, offers the lowest cost of all, but it imposes additional requirements on the CWP.

Variations in the actual cost of the various SKSS concepts around their estimated cost is taken into account. Three alternative cost scenarios are formulated by increasing or decreasing the estimates of major component cost items to yield respectively low, medium, and high cost cases for each SKSS design, these cost scenarios are then used to compute life cycle cost (LCC). Variation in chain and wire rope service life, machinery costs, and weather downtime during deployment are treated; results are given at the bottom of Table 3-6.

Table 3-7 lists the life cycle costs calculated for the eight SKSS concepts under consideration. The expected value LCCs of the four MAL type SKSS for the barge platform are clustered quite closely together, and their costs can thus be regarded as being equivalent for all practical purposes. The SAL SPM offers substantially lower costs; this concept seems unlikely to meet major design requirements. The SKSS designs prepared for the spar platform have lower LCCs. The TAL concept appears to offer significant cost advantages over the MAL SPM spread moor, amounting to nearly a third of the latter's cost. As noted before, the savings shown for the TAL does not take into account the impact on the CWP required by this concept. The two TAL systems appear to be subject to the greatest cost uncertainty among the concepts considered; their high cost case estimate being over double that given for the low cost scenario.

Table 3-6 CONCEPT DESIGN COST ESTIMATES (1979 \$K)

Component & Life	SAL SPM Ship	MAL Spread Spar	MAL Spread Ship	MAL Active Tension- ing Ship	MAL Turret Ship	MAL SPM Ship	TAL Spar	TAL Monopod Ship
Chain	230	2,101	4,682	4,682	2,160			
Wire Rope and Connectors	237	2,061	4,510	4,950	2,705	5,695		
Mooring Base/ Anchors	3,350	435	547	547	328	891	4,237	4,237
Mooring Buoy	6,185					2,380		
U-Joints	825						700	350
Yoke	1,525							
Tri-Axial Swivels	980							
Shackles and Stoppers		62						
Hawse Assembly		5,211						
Auxiliary Machinery			3,210	4,167	3,210	3,370		
Turret Assembly					6,575			
Hawsers						76		
Vetco Connectors							138	140
Tension Leg							2,478	
Engineering Labor	932	655	800	971	1,228	1,006	460	365
Deployment	11,000	11,500	11,500	11,500	11,500	11,500	10,250	8,000
TOTAL-Baseline	25,264	22,025	25,249	26,817	27,706	24,918	18,263	13,092
TOTAL for Cost Scenarios:								
Low	21,859	19,161	22,573	24,045	23,737	21,954	15,293	11,068
Medium	27,498	24,640	28,251	29,819	30,330	27,218	20,313	14,692
High	41,381	38,044	41,665	43,424	45,952	40,506	32,811	26,547

Table 3-7 SKSS CONCEPT LCCs (1979 \$K)

	Cost Scenario			Expected Value
	Low	Medium	High	
<u>Ship Platform</u>				
SAL SPM	33,448	41,984	62,587	45,000
MAL MPM	39,764	50,781	75,382	54,177
MAL Active Tensioning	45,352	53,881	79,245	58,090
MAL Turret	38,268	49,866	75,464	53,366
MAL SPM	39,657	53,234	77,039	55,791
<u>Spar Platform</u>				
MAL MPM	31,140	40,715	62,508	43,770
TAL	22,723	30,067	48,158	32,753
TAL Monopod	16,530	21,856	38,880	24,780

Cost Equivalence of Operational Failures

A second type of SKSS-related costs which cannot be included directly in the LCC are the costs incurred as a result of SKSS component failure in the course of OTEC operations.

Operational failures requiring major repair operations and/or plant downtime, and catastrophic failures, possibly leading to loss of the OTEC plant are considered. In the case of the MAL events such as mooring leg breaks or anchor dragging would probably result in plant shutdowns until repair can be effected, but are unlikely in themselves to threaten the survival of the OTEC platform, given the redundancy inherent in such systems. This is not the case for SAL or TAL SKSS designs, however. Major failure in the SAL components of these systems would result in loss of stationkeeping capability, which may well result in loss of the entire OTEC plant, particularly as such failure is likely to occur in the course of storms. The relationship between cost and both major remedial and catastrophic failure occurrences due to the stochastic nature of these occurrences, and to the wide range of physical events and

conditions they encompass, is discussed to provide a rough estimate of the cost impact of such failures.

A large component of the overall cost of failures resulting in significant plant downtime is the cost of foregone electricity sales. For a 40-MW(e) plant, operating at a capacity factor of 0.80 and selling electricity at a (levelized) price of 65 mils/kWh, this cost is approximately \$1.5 million/month. It is assumed that approximately one month is a reasonable lower bound for downtime resulting from a serious SKSS failure, and 6 months is assumed to be the highest likely downtime for SKSS repair. Thus, the associated cost of foregone electricity sales is somewhere between \$1 and \$9 million. The cost of the SKSS repair itself depends on the specific failure mode involved, and could easily be quite high, because it may involve retrieval of anchor legs and riser cables from the ocean bottom, and/or major component replacement; the cost of required support craft is expected to account for the majority of these costs. As a rough estimate, overall repair costs are assumed to be half of original deployment costs, or approximately \$1 to \$2 million for the SKSS concepts discussed here. Combining this estimate with that for foregone electricity sales yields an overall estimate of failure-related costs of between two and \$11 million. Thus a rough-order-of-magnitude cost of \$7 million (1979) is associated with the occurrence of a "typical" SKSS failure requiring extended shutdown of the OTEC plant.

As mentioned before, the type of failure considered above, which for a MAL may lead to a plant shutdown until repairs are completed, for a SAL or TAL type SKSS could result in plant loss. In the latter event, the costs incurred are equal to the market value of the plant; this market value cannot be evaluated a priori but, in view of the assumed continuous inflation, it is likely to be of the same magnitude in nominal terms as the original capital cost of the plant. For a prototype 40-MW(e) plant, this cost is likely to be \$5000/kW(e), or approximately \$200 million (in 1979 currency). This huge potential loss can be prevented by a relatively moderate investment in emergency backup equipment such as an auxiliary mooring system.

Of course, the effect of failure on expected LCC depends also on the probability and time of occurrence of such failures. While no statistically relevant body of data on mooring system failure has been found, informed opinion suggests that SKSS concepts meeting design requirements are likely to provide high reliability, with (subjectively estimated) failure probabilities over their lifetime in the range of 0.1 to 0.2. Assuming that a failure were to occur, the probability distribution of its time of occurrence is likely to be skewed toward the later years of operation; it is conservatively assumed that such failure will occur during the fifteenth year, the midpoint of the plant's operational life. Multiplying the estimated failure costs by a probability of occurrence of 0.15 and then discounting the expected costs back to 1979 yields an equivalent present cost of roughly \$0.7 million for the "typical" serious failure, and of \$20 million for the catastrophic failure. These figures can then be compared to the LCCs to assess the likely impact of failure costs on actual SKSS LCCs.

Somewhat surprisingly, the expected present value of the cost of a noncatastrophic failure, such as could be experienced by the MALs, is not very large in comparison with most SKSS LCCs and averages roughly 2 percent of these costs. This suggests that only major improvements in reliability are likely to justify the selection of higher-cost SKSS systems for use with OTEC platforms with respect to cost; safety and program continuity must also be considered. The expected present value of catastrophic failure costs is much larger, amounting to roughly one half of overall SKSS LCCs. This simply shows that the possibility of such failure should be minimized, perhaps by the addition of emergency backup equipment as discussed above. In this context, it is noted that the expected present cost of catastrophic failure is roughly three times higher than the investment required to significantly reduce its probability of occurrence, thus clearly justifying such investment.

3.6 SKSS CONCEPT EVALUATION AND RANKING

Candidate SKSS concepts are evaluated in terms of performance, cost risk and required development. The relative risks of each concept are compared with

life cycle cost and a ranking is established. A second ranking based on extent of technology development concludes this section (Ref. 2, Sec. 3).

3.6.1 Performance Assessment

Single Anchor Leg-Single Point Moor. The primary flaw in this concept is the unavailability of a single-wire rope, synthetic line, or hollow cylindrical link construction with proven capabilities to handle the anchor leg tension in the Extreme Sea State. Extensive development of such lines is required before this concept can be considered feasible. The alternative is to lower the line tension safety factor from 2 to 1, a high risk solution at best. Anchor deployment must also be developed. The second design has an excessive watch circle of 23 percent water depth; spar buoy submergence and yoke angle are excessive in the Extreme Sea State. This system is sensitive to errors in anchor depth. Clearance of CWP and tension leg is of critical concern. The relatively small excursion in the Extreme Sea State prevents CWP grounding, leading to consideration of a reduction in mooring depth from 4000 to 3300 ft with associated cost reduction. Positive features of this system are barge weathervaning capability and system removal via the stab-in device at the base, for survey and replacement.

Multiple Anchor Leg. The concept satisfies all design criteria and requirements and is therefore considered feasible within present state of the art. The stand-off buoy riser cable is selected over the catenary direct descent concept for this system, allowing a watch circle of 18 percent water depth as opposed to the design requirement of 10 percent. Consideration must be given to the clearance between the anchor legs and riser cables. Clearance of anchor legs and power modules is a concern for application to the spar. Long term performance of wire rope is a concern.

Multiple Anchor Leg - Single Point Moor. This concept appears to satisfy the design requirements. However, development of the unconventional multiple, parallel line concept is required to demonstrate assumption of equal-load division among the lines. A base swivel is not acceptable due to the imposed

requirement for a submerged swivel in the ETS which is well beyond SOA. Deployment and removal of a large gravity anchor, although considered feasible, requires a development program. A catenary, direct descent with surface swivel riser cable is used with this system commensurate with the ten percent-water-depth watch circle.

Multiple Anchor Leg - Turret. This system satisfies the design criteria and is considered to be feasible. Considerably greater interfacing is required compared with the MAL concept. The discharge pipes interfere with the anchor legs, requiring relocation of these pipes to the barge ends or discharging in a pipe concentric with the CWP. The significant benefit gained is the ability to fully control ship heading, leading to potential reductions in ship motions as well as anchor leg loading in comparison with the non-azimuthing concepts. Plant power is required for the thrusters, included in the barge, to provide yaw moment to turn the platform into the desired heading. Once a desired heading is achieved, the thrusters are stopped and the turret is locked in position. An electrical swivel may not be required if riser cable rotation is restricted to less than 180 deg.

Multiple Anchor Leg-Active Tensioning. The concept satisfies the design requirements and is considered feasible. Partial heading control is realizable, with some reduction in motion and loads. An additional feature is the ability to provide for load equalization. Plant output is required intermittently to power the winches. An electrical swivel in the ETS is not required with this concept.

Tension Anchor Leg. The concept satisfies the design criteria and requirements and is considered feasible with qualifications. A significant flaw in performance is submergence of the spar completely below the water surface in storms. The TAL imposes tensile and bending moment loads on the CWP which must be considered in the CWP structural design process. Other considerations include sensitivity to errors in base depth and lack of component redundancy. Since the CWP inlet position is well restricted, it is possible to moor the plant in shallower water, say 3200 ft depth. The vertical descent ETS is the most suitable concept for the TAL.

Tension Anchor Leg Monopod. The Monopod is similar to the TAL so that the above assessment applies to this concept. Spar submergence is not as great as in the TAL, so that the impact on the spar is less for the Monopod. The wave-induced bending moments in the CWP make this concept unattractive for the 40 mw(e) plant. If the mooring depth requirement is reduced then CWP extension would not be necessary. Both concepts provide for design simplicity and ocean system integration, and potential cost reduction.

3.6.2 Risk Versus Cost

The life cycle costs for each SKSS concept are added to the acquisition and deployment cost of the ETS best-suited to each SKSS. This is done to aid in ranking concepts; however, the final ranking is identical if ETS costs are excluded. The totals are divided by the largest total cost of \$66 million for the MAL-Active Tensioning. Similarly, the risk-criticality factors are divided by the risk for the SAL-SPM.

These normalized costs and risks are combined with a weighting factor having a range of 0 to 1. The sum is interpreted as a relative figure of merit, and provides a cost-risk basis for ranking the concepts. A low weighting reduces the importance of cost and increases the significance of risk while the opposite holds for a high weighting factor. The results for the Barge SKSS are that the MAL-Turret ranks first for all cases except that which ignores risk ($W=1$). The Spar TAL concept ranks highest for cost equal to or higher in importance than risk. In the case where risk is more significant than cost, the MAL ranks first and the TAL second (see Fig. 3-8).

3.6.3 SKSS Technology Assessment

The SKSS concepts are next ranked according to the extent of development required to advance the state of the art in deep ocean mooring technology. The ranking factors used to assess OTEC technology are as follows:

Fig. 3-8 Life Cycle Cost Versus Risk Criticality

<u>Score</u>	<u>State of the Art</u>
10.	Technology is nonexistent
9.	Massive high-risk R&D
8.	Extensive relatively high-risk R&D
7.	Extensive moderate-risk R&D
6.	Nominal moderate-risk R&D
5.	Limited offshore experience
4.	Nominal low-risk R&D
3.	Relatively little R&D requiring no testing
2.	Little R&D and no testing
1.	Existing Technology fully adequate

A high score indicates that extensive technology development is required. The anchor leg, mooring leg, anchor, swivel and deployment are evaluated in terms of current state of technology. The mooring leg is applicable to the SAL-SPM and MAL-SPM; a score of 10 for the other concepts indicates that these systems do not require a mooring leg. Existing technology (Table 3-8) is most nearly adequate for the MAL and least adequate for the SAL-SPM; the MAL is ranked first, with the MAL-Active Tensioning and MAL-Turret a close second and third, respectively.

Table 3-8 SKSS TECHNOLOGY DEVELOPMENT

SKSS Concept	Anchor Leg	Mooring Leg	Anchor	Swivel	Deployment	Total	Rank	
							Barge	Spar
SAL-SPM	8	4	6	2	7	27	5	
MAL	4	1	1	1	2	9	1	1
MAL-Turret	4	1	1	4	2	12	3	
MAL-Active Tensioning	5	1	1	1	2	10	2	
MAL-SPM	5	4	6	2	7	24	4	
TAL	7	1	3	2	4	17		2
TAL-Monopod	7	1	3	2	4	17	4	2

(1) 1-Favorable, 10-Unfavorable or N.A.

Section 4

PRELIMINARY DESIGNS

4.1 MULTIPLE ANCHOR LEG SKSS FOR OTEC BARGE

The preliminary design of the multiple anchor leg SKSS with active tensioning for the OTEC barge is presented in this section. An engineering description of the system is followed by system loads analysis, performance evaluation, installation requirements sensitivity, and Commercial Plant SKSS (Ref. 5).

4.1.1 Engineering Description

The barge Stationkeeping Subsystem (SKSS) is a catenary multiple anchor leg (MAL) mooring with active tensioning. The active tensioning feature allows for variation of the anchor leg geometry by lengthening or shortening anchor legs and load transfer from each leg to an attached pendant. The latter provides for barge heading control.

General Arrangement. The MAL is comprised of eight catenary anchor legs arranged in pairs at each corner of the barge. One leg of each pair lies in a vertical plane at 45 deg to the barge centerline, and the second at 15 deg from the beam, providing fore and aft symmetry with respect to included angle. A general arrangement showing the anchor leg configuration is given in Fig. 4-1.

The first four anchor legs are oriented seaward, while legs 5 through 8 are landward. Anchors on the longer seaward legs have a 1,000-ft greater range and are set at a depth 2,400 ft greater than that on the landward legs. This asymmetry is a direct result of the sloped sea floor at the site. The seaward anchors and chain rest on the sea floor sloping down from the leg; conversely, the landward anchors and chain rest on the up slope.

Each anchor leg consists of chain, wire rope, and a pair of drag embedment anchors. The upper segment chafing chain passes under a fairlead on the barge side to a wildcat on a deck-mounted windlass and down to a chain locker below the main deck. A chain pendant is attached to the anchor leg at the chafing-chain/wire-rope connection and secured at the barge keel. The scantlings of each leg are identical, while wire rope and lower chain segment lengths vary between legs. Anchor leg component details are shown in Fig. 4-2.

A pair of drag-embedment anchors is attached to each anchor leg in series. Each anchor weighs 60,000 lb with fluke angle dependent on as-measured soil conditions. Anchor holding-power-to-weight ratio is 20 in sand with a penetration angle of 34 deg, a minimum depth of 7 ft, and a scope angle of zero.

The anchor chain is stud link chain, 4-7/8-in. diam, Grade 4. Proof test load is 2,052,000 lb, and break test load is 2,932,000 lb. The dry weight is 229 lb/ft.

The anchor chain segment below and the chafing chain segment above are connected by the wire rope segment. The length of each wire rope segment varies from 2,800 to 3,100 ft depending upon anchor leg location, while the diameter is constant for all legs at 5-3/4 in. The wire rope construction is six strands, right hand regular lay, each strand consisting of 97 steel wires (6 x 97). At the center is an independent wire rope core (IWRC). Wire rope material is extra improved plow steel. Preloading of the wire rope is recommended to extend fatigue life. Wire rope weight is 65 lb/ft; the design breaking strength is 3,000,000 lb. The apparent modulus of elasticity is 12,780,000 psi, with a steel area of 61 percent of the enclosed area. The wire is zinc galvanized and blocked with a petrolatum-based grease or synthetic infill to retard the onset of corrosion.

The upper segment of each anchor leg consists of a 700-ft continuous length of 4-7/8-in.-diam stud link chain. The deck machinery on the barge dedicated to the MAL consists of a fairleader, windlass, and chain locker for each of eight

4-3/4-4

Fig. 4-2 Multiple Anchor Leg Component Details

anchor legs. In addition, a power unit and control panel for each windlass pair and a central control unit is provided (Fig. 4-3).

4.1.2 Loads and Performance Prediction

Environmental loading on the barge is based on the quasi-static force and moment analysis presented in Ref. 2. The results in Table 4-1 indicate the resultant horizontal-plane force and yaw moment on the barge, assuming coplanar wind, wave, and current. The force increases approximately 50 percent as the loading rotates from head to beam. The force in the Extreme Sea State is 130 percent greater than that in the Operational Sea State.

The yaw moment on the barge is sensitive to relative heading between barge and storm. The yaw moment, maximum at 10 deg off the bow, is a restoring moment for headings from 0 to 45 deg.

The MAL induces net moments on the barge which result in trim about the transverse axis, heel about the longitudinal axis, and yaw about the vertical axis. The magnitude of these angular changes are examined for the Extreme Sea State. Bending and torsional moments, also induced by the anchor legs, are not treated.

The maximum heeling moment occurs in the beam condition and is 270×10^6 ft-lb. This moment causes the barge to heel 8.4 deg into the oncoming wind, thereby reducing the freeboard on the weather side by 8.9 ft and leaving a net freeboard of 15.1 ft. Barge trim is insignificant. The MAL provides a restoring moment about the barge vertical axis, or yaw moment, which is balanced by the applied sea state moment. The yaw offset for quartering seas is -9 deg; the barge rotates into the sea state so that the resultant sea-state heading is 36 deg.

The natural frequencies of the MAL in surge and sway are shown below.

Motion	Natural Frequency		Natural Period (sec)
	(Hz)	(rad/sec)	
Surge	0.002	0.014	458
Sway	0.003	0.0188	334

In the event that resonance occurs, the system is sufficiently damped to preclude oscillatory motion. The ratio of total to critical damping is 1.54, indicating that MAL damping is large and motion will decay in less than one cycle of surge.

The tension-fatigue study shows that there is more than adequate fatigue life for the wire rope in part because the cyclic tension amplitudes that occur are well below the endurance limit associated with the cycles to failure. It is assumed that the wire is adequately protected so that corrosion does not occur. Actual tension-tension, cyclic corrosion fatigue data for wire rope is required to predict fatigue life. Dynamic tensions in the No. 1 anchor leg induced by barge motion, obtained for the maximum operating and survival conditions in both beam and head seas, are presented in Table 4-2; the largest significant dynamic tensions are shown. Maximum total tension occurs near the top of the anchor leg, while maximum dynamic tension occurs near the bottom.

The MAL is required to constrain the barge within a watch circle of 400-ft radius in sea states up to and including the Operational Sea State of 3-year return period. The MAL satisfies this requirement as indicated by the results in Table 4-3. The locus of barge excursion, shown for the second quadrant in Fig. 4-4, is a maximum of 340 ft at 23 deg with the sea state at 45 deg. MAL stiffness is greater in the longitudinal than transverse directions.

MAL performance in the Extreme Sea State is summarized in Table 4-4. The tension safety factor for beam and head loading exceeds the criteria by 20 percent, allowing for dynamic tension component due to leg oscillations and

Table 4-1 SUMMARY OF ENVIRONMENTAL LOADS ON BARGE

Item	Operational Sea State		Extreme Sea State	
Storm Return Period (yr)	3	3	100	100
Heading (deg)	90	0	90	0
Wind Force (10^6 lb)	0.05	0.08	0.17	0.26
Current Force (10^6 lb)	0.21	0.30	0.37	0.53
Wave Force (10^6 lb)	0.12	0.31	0.44	0.81
Net Force (10^6 lb)	0.38	0.69	0.98	1.60
Net Moment (10^6 ft-lb)	0.42	-0.98	1.4	-1.4

Coplanar Wind, Wave, Current

Table 4-2 ANCHOR LEG DYNAMIC TENSIONS

Sea Condition	Heading	Max. Dynamic Sign. Tension (lb)	Max. Total Tension (lb)
Operational Sea State	Beam	47,966	1,048,000
Operational Sea State	Head	74,454	1,100,000
Extreme Sea State	Beam	158,967	1,255,130
Extreme Sea State	Head	151,352	1,463,500

Table 4-3 MAL RESPONSE IN OPERATIONAL SEA STATE

Seaway Heading (deg)	Seaway Force (10^6 lb)	Longitudinal Excursion (ft)	Lateral Excursion (ft)	Excursion (ft)	Leg No. 1 Tension (10^6 lb)	Safety Factor
0	0.38	-291	3	291	1.04	2.9
45	0.60	-314	-132	340	1.14	2.6
90	0.69	2	-249	249	1.07	2.8

Fig. 4-4 Barge Excursion in Operational Sea State

dynamic amplification of drift response. On the intermediate headings, however, the safety factor is less than the minimum of 2. The leg lengths are therefore increased on the most highly loaded legs (see Fig. 4-1), realizable by the active tensioning capability, resulting in a safety factor of 2.2 (see Table 4-4). Although platform excursion is greatly increased from 704 to 1,157 ft, there is adequate depth below the CWP inlet to ensure clearance with the seafloor. In the high excursion of the Extreme Sea State and with active tensioning the unloaded, "down-wind" legs are slack. The vertical portion of

Table 4-4 MAL RESPONSE IN EXTREME SEA STATE

Seaway Heading (deg)	Seaway Force (10^6 lb)	Longitudinal Excursion (ft)	Lateral Excursion (ft)	Excursion (ft)	Max Tension (10^6 lb)	Minimum Safety Factor
0	0.97	-656	17	656	1.34	2.2
30	1.33	-714	-182	737	1.64	1.8
45	1.50	-635	-304	704	1.69	1.8
45	1.50	-1,075	-427	1,157	1.34	2.2 ^(a)
90	1.61	6.7	-514	514	1.38	2.2

(a) Active Tensioning

this leg poses potential interference problems with at the chafing chain on the hull side and with the wire rope segment on the lower portion of the CWP. Horizontal deflection of the CWP in this sea state is required to evaluate the potential for interference between the CWP and anchor leg.

The anchors provide sufficient holding power to prevent slippage in the Extreme Sea State. The holding power of the chain length resting on the seafloor (minimum length of 1,341 ft) is ignored. Anchor holding power safety factor is equal to 3 if the efficiency of the second anchor is assumed to be 70 percent of the first anchor's efficiency. If the seafloor is composed of clay instead of sand, then the safety factor is 1.5.

Active Tensioning

Survivability in the Extreme Sea State as measured by SKSS redundancy is examined in the highest loading condition of a 45-deg sea state heading. The highly loaded leg No. 1 is assumed lost, and the resulting seven-leg MAL suffices. Platform heading is controllable to a limited extent by the MAL tensioning equipment. By virtue of the windlass, fairleader, and chain on the upper segment of each anchor leg, the leg lengths are variable by approximately ± 300 ft (landward legs) and $+400/-200$ ft (seaward legs).

The active tensioning system cannot be effectively utilized to adjust tension and heading simultaneously in the Extreme Sea State. Heading control is achieved by the transfer of load from the anchor leg to a pendant connected to the anchor leg and to a distant point on the barge. The heading control system facilitates a zero to 90-deg change of heading of the platform. The change is effected by sharing or completely transferring the tension from the anchor leg to a pendant. One end of the pendant is permanently attached to the end link at the wire tope to chafing chain connection. The other end is connected to a padeye on the platform keel below the adjacent anchor leg. Load transfer is accomplished by paying out the chafing chain on each leg until the pendant is taut and the chafing chain is slack. This arrangement permits turning the bow seaward from the initial Easterly heading in increments to a South Easterly heading as required. This is compatible with hurricane tracks passing to the South of the moored OTEC plant.

The MAL is equipped with the capability to alter the anchor leg lengths and thereby the leg tension. This capability is useful in the following areas:

- o Equalize anchor leg tension to reduce maximum tension and fatigue loading
- o Equalize anchor loading
- o Alter heading of barge in the seaway
- o Compensate for anchor slippage
- o Reposition chain on sheave
- o Inspection of upper segment of anchor leg

The first two areas are illustrated in the preceding sections, for the Extreme Sea State, wherein the required safety factors are obtained by length changes in selected legs. The control of heading is then shown to be feasible by pendants which are loaded by paying out all anchor legs, effectively transferring the anchor leg loads to a distant point on the barge, thereby turning the barge within the array of anchor legs.

Operation of the MAL active tensioning SKSS is controlled from the bridge by a central control unit. Active tensioning is initiated when monitoring of the anchor leg tension shows that mean tensions are rising and approaching or exceeding the safety factor for the existing sea state. A prescribed sequence of pay out and reel in steps are followed until the tensions are adjusted. The operation is initiated by starting the windlass, taking the load on the windlass, releasing the chain stopper and powering the windlass for pay out or reel in. A length change of 100 ft is made in 10 minutes, while the sequence of changes is expected to be 1 hour or more in duration. Control stations at each corner of the barge provide for local operation of the windlass pair at the corner. If heading adjustment is required, then all windlasses are activated to pay out the necessary length of chain to achieve the desired rotation. Barge heading is adjusted as required if for example the wave direction shifts during a storm. These operations are expected to be routine in sea states up to and including the Operational Sea State.

Active tensioning and heading control in the Extreme Sea State requires adequate forecasting of the approaching hurricane. Barge heading is adjusted as required to place the barge "head-to" these oncoming waves. If the barge is not abandoned and if the eye passes the barge, the MAL active tensioning system may be engaged to readjust the barge heading as required. Note however that the seaway is then likely to be a multidirectional, confused sea, so that desirable barge heading is less clearcut. If the barge is abandoned, then the system is left in the most favorable condition of heading and leg tension distribution. In trading the benefits of heading and leg tension adjustment, the seaworthiness of the barge and particularly the necessity of maintaining a head seas orientation are compared with the MAL stationkeeping capability in a hurricane.

4.1.3 Installation

The deployment workbarge characteristics, deck equipment, and arrangement are shown in Fig. 4-5. The continuous pulling machine (Lucker Winch) for wire

rope provides maximum line tension of 1,400 kips while paying out wire rope at 10 fpm. The machine is reversible, allowing wire rope haul in at the same load and speed.

Deployment consists of workbarge loading at dockside, transit to and from the deployment site, anchor leg lowering, and anchor setting. The anchor lowering operation is estimated to require 15 hours. The procedure to deploy the first anchor leg is as follows:

1. The loaded workbarge is moored alongside the platform outboard of the anchor leg fairlead.
2. The two anchors with the 100-ft connecting chain is lifted by the platform pedestal crane and hung overboard by the anchor chain on the windlass.
3. A 170-ft length of wire rope is connected to the chain from the platform windlass. The rope is placed in the grips of the linear winch for pay out from the workbarge.
4. Mooring lines are released. The workbarge is headed out to sea under the anchor drop point while the 170-ft wire rope is payed out. Tugs assist moving the platform and barge.
5. Anchor lowering via the windlass commences as soon as the workbarge is headed out to sea.
6. Connection is made between the 170-ft wire rope and the wire on the storage reel with an end link between the wire rope sockets. Pay out of wire rope commences from the storage reel.
7. Pay out of wire rope through the linear winch continues until the storage reel is emptied. The wire rope is then secured while the workbarge is acoustically positioned for anchor lowering.
8. Final acoustic positioning is established before anchors are lowered to the seafloor.
9. Monitoring the load sensor on the windlass, the anchors are landed in sequence while paying out chain and moving toward the platform. The anchors are set subsequent to landing and before entire chain length is on seafloor.

10. The chain stopper is engaged when the wire-rope-to-chain connecting link is above the stopper.
11. The wire-rope-to-chain connection is made, operating the linear winch as necessary to facilitate the connection.
12. The load on the linear winch is relieved and the grips of the winch are reversed for passing wire rope in the opposite direction.
13. The load is transferred from the chain stopper and the windlass to the linear winch.
14. The workbarge is powered toward the platform with the winch and thrusters until the wire rope socket-to-socket joint with the 170-ft wire rope is just below the windlass wildcat. The wire rope is then secured by the linear winch and the wire rope stopper.
15. The workbarge is moored alongside the platform, and the slack chain is disconnected from the wire rope.
16. The chain is payed out from the platform windlass along the workbarge deck and connected to the end link between the wire rope sockets outboard of the windlass.
17. The wire rope stopper is opened. The wire rope is payed out with the linear winch to transfer the load from the wire rope to chain.
18. The chain is hauled in while the workbarge is moved inboard and to port of the anchor leg. When the chain lifts off from the workbarge deck, the chain is hauled in as required to facilitate disconnecting the 170-ft wire rope from the end link.

Deployment of the second up to the eighth leg is identical to the above procedure except for the insertion of the auxiliary wire rope between the 170-ft and the storage reel wire rope segments. This alters the procedural steps between 6 and 7. After each leg is deployed, the workbarge returns to port for dockside loading of the next leg to be deployed. The line tensions in the equilibrium (no environmental load on platform) condition provide the leg tensions that are realized for proper anchor set. Platform station is maintained by tugs until MAL installation progress is sufficient to permit removal of the tugs. A standby tug is provided throughout the deployment sequence to provide emergency bollard pull in the event of power loss on the workbarge.

The MAL SKSS is to be removed from the seafloor at completion of the 30-year service life. The anchor leg retrieval procedure is a modified version of the changeout procedure combined with a modified reversal of the initial deployment procedure. The workbarge is arranged as for deployment but with the supply storage reel empty.

4.1.4 Inspection, Maintenance, and Repair

Inspection of elements of the stationkeeping subsystem which are installed on the platform or are situated above the waterline permit simple periodic visual examination of the anchor windlass equipment and the mooring cable running to the waterline. Inspection of the elements below the waterline is accomplished by divers, or by manned or remotely controlled submersibles. The primary tool for deep underwater inspection is a remotely controlled submersible. A limited diver capability, part of the crew structure to accomplish underwater inspection of the platform, is also used for shallow water inspection of each anchor leg with a hand held TV camera.

The third tool, a magnetic inductance vehicle, provides for NDT inspection. The tool, readily attached to the anchor leg, is lowered down the leg and retrieved while providing readouts of wire condition. This tool is under development by Noranda of South Yorkshire, England.

SKSS equipment installed on the platform is maintained and repaired in the manner prescribed by the manufacturer. The schedule for such maintenance is also in accordance with the manufacturer's instructions. The machinery controlling each anchor leg is, except for the exceptionally high load requirements, common to the marine industry and thus introduces no new or extraordinary maintenance tasks. Except for stress relief and the maintenance prescribed for portions of the chafing chain below the waterline no other maintenance is applied to the legs.

Because of the depths involved it is impractical to consider that effective repairs can be made to an anchor leg other than by replacement of the failed or degraded element. The procedure to accomplish replacement of the wire rope is a modified reversal of the initial deployment procedure.

4.1.5 Interfaces

The windlasses require platforms which extend the main deck 9 ft at each corner of the barge. These windlass platforms interfere with the deckhouse in the aft portion by as much as 9 ft. Platform structural scantlings below the platforms must be increased to support the weight and mooring loads. The large fairleaders on the barge sides require adequate foundation structure as well. Barge primary structure may require modification as a result of bending moments and shear induced by the anchor legs. Below deck the chain lockers interfere with certain spaces between the main deck (El. 89) and the second deck (El. 65). Aft on both sides the chain lockers interfere with electrical and engineering workshops (El. 65) and future electrical spaces (El. 77). The chain lockers forward interfere with platform equipment and thruster access spaces port and starboard.

The anchor legs are generally well clear of the CWP in all but the Extreme Sea State. In this condition the active tensioning required to reduce leg tension causes leg No. 5 to be "slack" (see Fig. 4-1). This leg is "down current" and is 275 ft from the CWP inlet. The leg and CWP will touch if the CWP deflects in the current and or the dynamic oscillations of CWP and MAL are of sufficient magnitude and phasing to result in relative motion of 275 ft. This leg is essentially vertical at the platform so that the chafing chain is likely to contact the barge side plating.

The watch circle of the barge is restricted by the allowable bend radius and tensions in the riser cable. Riser cable concepts compatible with the MAL are presented in Section 3.3. Direct descent catenary risers attached to the barge on the landward, port side and descending to the seafloor between anchor

legs 6 and 7 provide the least potential for interference between the MAL and ETS. The distance between the anchors on these legs is 2,800 ft. The touchdown point of the anchor legs is 1,700 ft to seaward of the riser cable touchdown point, minimizing cable-anchor leg interference.

4.1.6 Sensitivity to Requirements

MAL sensitivity to errors in environmental load magnitude is examined by assuming that the wave drift force is exceeded by 25 percent of the design mean wave drift force in the Extreme Sea State. The resultant safety factor is 2 with active tensioning applied to reduce anchor leg tension, and 1.6 without active tensioning. In addition, other loads of lesser magnitude such as vortex-induced loads on the anchor leg require further investigation in establishing anchor leg fatigue life. While the MAL has sufficient strength for loads higher than the design loads, the design safety factor is not realized for loads in error by more than 25 percent of wave drift force, or 10 percent of total sea state force.

The effect on the MAL of increasing water depth is to increase the anchor leg length. The longer the anchor leg, the greater the vertical component of tension at the barge. This penalizes the MAL since a greater fraction of the wire and chain breaking strength is required for self weight. The limiting depth is the depth at which the chain can just support its weight. It is estimated that the limiting mean depth for the MAL is approximately 5,100 ft. This depth is greater if the sea floor is not sloped.

The MAL is designed to constrain barge excursion to less than 400 ft in the Operational Sea State. Maximum excursion is 340 ft with a horizontal tension component of 300,000 lb. If the watch circle requirement is made less restrictive, this tension can be reduced with an equivalent reduction in anchor leg scantlings. For example, doubling the allowable excursion to 800 ft, or 20 percent of water depth, reduces the horizontal tension to 100,000 lb, or a 67-percent reduction of the design value. This leads to a 23-percent reduction in maximum tension if wire rope and chain size are

unchanged. A reduction in the vertical tension component is achieved by reducing the cross-section of wire and chain. Although some reduction in scantlings is realized, the requirement to provide an adequate safety factor in the Extreme Sea State remains. There is relatively little sensitivity of MAL size and cost to allowing greater watch circle, unless the watch circle is significantly increased.

4.1.7 Commercial Plant SKSS

The principal characteristics of the commercial barge concept specified for the study are given in Table 4-5. Sea States and site are assumed to be identical to the specifications for the smaller OTEC barge. A summary of the environmental loads on the ship, presented in Table 4-6, shows the applied force is approximately three times that on the smaller barge.

The MAL design has adequate strength and holding power to hold the Commercial Plant in Sea States of return period of 3 years and less, with watch circle excursion of approximately 704 ft or 18 percent of depth. In higher Sea States the greater loads on the Commercial Plant would result in both overstressing the anchor legs and anchor slippage.

A design approach to the Commercial Plant MAL is to increase the number of legs from eight sufficiently to carry the loads, without increasing the breaking strength of each leg. A first estimate of the number of legs for this concept is 24, or an increase of 16 legs. Although this approach requires minimal extension of manufacturing capability, it does impose an unrealistic requirement for operation and maintenance of 24 windlasses. The deck machinery is not required if the active tensioning feature of the MAL is not necessary for the Commercial Plant. To effectively develop the SKSS, the requirements of the Commercial Plant SKSS, assumed here to be that of the smaller pilot plant SKSS, must be determined. In particular, the need for active tensioning requires consideration and comparison with potential benefits. The large beam of the Commercial Plant, significantly greater than that of existing platforms of comparable length, affects response in a seaway,

Table 4-5 PRINCIPAL CHARACTERISTICS OF THE 400-MW (NET)
BARGE OTEC PLATFORM

Length	620 ft (189m)
Beam	300 ft (91m)
Depth	85 ft (25.9m)
Draft	45 ft (13.7m)
Operating Displacement	310,000 L.T. (314,900 metric tons)
Cold Water Pipe Inside Diameter	100 ft (30.5m)

Table 4-6 COMPARISON OF COMMERCIAL PLANT VS. PILOT PLANT LOADS

Heading	Sea State Return Period (years)	Force (10 ⁶ lb)		Yaw Moment (10 ⁶ ft-lb)	
		Pilot	Commercial	Pilot	Commercial
Head	3	0.38	1.22	-	1.1
Head	100	0.97	3.06	-	3.8
Beam	3	0.69	1.86	-1.0	-1.9
Beam	100	1.61	4.75	1.3	-2.7

so that motions in a beam sea, for example, must be compared to head sea response to assess the heading most favorable to motions and accelerations.

A hardware development program for the Commercial Plant MAL is not recommended at this time. Definition of SKSS performance and operation requirements is necessary before component sizing and development needs can be identified to assess the requirement for active tensioning. A scale model test program is recommended. The objective of conducting these tests is to determine the importance of plant heading on seaway response. In the event that these tests indicate responses are relatively insensitive to heading, the requirement for heading control and for the extensive deck machinery is reduced or entirely removed.

4.2 TENSION ANCHOR LEG (TAL)

The TAL is selected for the spar stationkeeping subsystem. Preliminary design of the mooring base and universal joint are presented, followed by loads analysis, installation and sensitivity to requirements (Ref. 4, Ref. 5, Section 3).

4.2.1 Engineering Description

A general description of the TAL is presented in Section 3.2.2; the mooring base and universal joint are described in greater detail in this section.

A CWP designed by Brown and Root for a TAL mooring system, is furnished for this study. Each section is made of a stiffened cylindrical shell. The sections are connected by universal joints of an unspecified design. The CWP sections are of varying length with the longest sections closer to the bottom. The following information on the CWP is provided:

Structural weight	15,000 kips
Net buoyancy	6,000 kips
Buoyancy tanks	8 ft x 15 ft (diam) x 200ft (length)
Buoyancy tank weight	2,400 kips

Since the water depth for the preliminary design is reduced from 4,000 to 3,280 ft, the lengths of the CWP sections are reduced. The CWP geometry and characteristics are shown in Fig. 4-6.

Mooring Base. The gravity-type mooring base is designed to counteract the greatest expected vertical and horizontal forces with a specified safety factor. The base structure, shown in Fig. 4-7 is 120 ft in diameter and 30 ft high. It consists of a bottom plate, a cylindrical outer shell, a central tube, and eight vertical radial bulkheads. The plates are lined with

Fig. 4-6 TAL CWP and Buoyancy Tanks

Fig. 4-7 TAL Gravity Base

LMSC-D677804

stiffeners. The base is filled with cement grout for ballast. Shear skirts project from the base bottom base into the soil are arranged in a matrix pattern. The guide tube for the installation of the CWP and universal joint is not shown.

The controlling factor in determining the diameter of the base is the bearing stress the soil can withstand without failure. The weight of the base plus ballast is sufficient to hold the vertical load (12,000 kips) with a safety factor of 1.5 and to resist sliding along the seafloor with a safety factor of 2.0. The design horizontal load is 1500 kips. The base structure is designed using the ABS rules for allowable stress levels.

Base Universal Joint. The base universal joint (Fig. 4-8) connects the lower end of the CWP to the center of the gravity base. The joint, with two angular degrees of freedom, is designed to pitch at least 30 percent in any direction, 10 deg of which is required for the sloping seabed. If the seabed slopes more than 10 percent at the site, the universal joint design is unaffected, provided that the central tube in the mooring base is tilted to the vertical.

The pedestals of the universal joints, fabricated from steel plate, are provided with press-fitted, self-lubricated bushings to transfer radial and thrust loads. Journal surfaces in contact with the bushings are protected against corrosion by a weld deposited overlay of Monel.

The universal joint material is mild steel, such as ABS grade E with a yield strength of 34 ksi. This eases welding of the large plate thicknesses of up to 8 in. Standard industry practice for the fabrication of large universal joints for tension anchor leg mooring systems is to use mild steel. An example of this is the Hondo field SALM, where the universal joints are of mild steel equivalent to A36, and weigh 60 tons each, to react a vertical load of approximately 1000 kips. The weight of the OTEC base universal joint is 300 tons; the vertical design load is 12,000 kips.

Fig. 4-8 TAL Base Universal Joint

A mechanical connection is provided for securing the bottom of the universal joint to the mooring base. This connector is similar to those manufactured by FMC or Vetco for offshore use as pile connectors. A specially designed unit is required for OTEC due to the large dimensions and loads. The lower portion of the universal joint has a stab-in tapered guide which, when coupled with guide wire equipment, allows for more positive positioning and securing into the mooring base during installation. The top pedestal structure is connected to the CWP extension by a conical shell. Lateral stiffeners are required at the ends of the cone to carry hoop stresses. Additional stiffeners may be required. The conical structure weighs approximately 90 kips.

4.2.2 Seaway Response

The spar-CWP acts as a vertical spring-mass system. Since the vertical wave forces are large, considerable heave resonance of the spar could occur. The heave of the spar is determined mostly by the spar mass, the vertical loads on it, the CWP spring stiffnesses, and damping.

The CWP stiffness is nonlinear; upward spar motion elongates the CWP shell and the universal joints, downward spar motion causes the CWP segments to fold at the joints and move laterally. The upward stiffness is determined by the cross sectional areas of the CWP shell and vertical stiffeners. In addition, the CWP joints contribute to the total axial stiffness. The joint stiffness is assumed to be the same as the stiffness of the CWP shell and stiffeners. The downward spring constant is approximated by dividing the CWP wet weight by its length.

The resulting simplified dynamic model of the spar-TAL used to estimate heave motion is shown in Fig. 4-9/ Two forces are considered as acting on the spring-mass system: (1) a constant vertical force corresponding to the net buoyancy of the spar-CWP, and (2) a time-varying force caused by the change in buoyancy of the column during the passage of waves, and by the wave loads on the spar. In the 100 year wave, the net maximum vertical force, including a

SPAR W	153900 K
	-1000 K
CWP	15000 K
INLET	1000 K
CWP BUOY	2400 K
WATER ADDED	30780 K
MASS	
TOTAL W	202080 KIPS
SPAR MASS =	6300 KSLUGS = M
K_u	= 4360 K/FT
K_L	= 4.5 K/FT

K_u = SPRING CONSTANT EQUAL TO AXIAL STIFFNESS OF CWP PLUS U.J.'S.COMPRESSION FORCE ONLY.

K_L = SPRING CONSTANT EQUAL TO WEIGHT OF CWP DIVIDED BY ITS LENGTH. COMPRESSION FORCE ONLY.

B = CONSTANT NET BUOYANT FORCE

$$F(t) = \sum F_i \cdot \cos \left(\frac{2\pi}{T_i} t + \phi_i \right)$$

D = DAMPING COEFFICIENT

Fig. 4-9 Spar-TAL Dynamic Model

coefficient of mass of 1.2, is 13,500 kips, which is much larger than the net buoyancy.

The horizontal loads on the spar and CWP in the Extreme Sea State are summarized as follows. Yaw moment is disregarded.

Component	Force (10^6 lb)	Design (10^6 lb)
Wind	0.08	0.14
Current		
(Spar)	0.36	0.65
(CWP)	0.13	0.13
Wave Drift	0.250	0.45
TOTAL		1.37

Sources of spar heave damping include:

- o Wave making resistance of the spar in heave
- o Drag on the spar
- o Friction in the CWP universal joints
- o Horizontal motion and drag on the CWP sections translated into vertical motion
- o Longitudinal drag on the CWP

Transverse drag on the geometry-dependent CWP sections is the largest source of damping. The damping constant of the spar-TAL can not be determined accurately for the simplified model used herein. Instead, the effects of a range of damping values are studied.

If the net buoyancy is much greater than the wave load amplitude, the CWP will not go into compression and the spar will act as a simple spring mass system. If the wave load amplitude is greater than the net buoyancy, the downward wave load can cause the CWP to become slack. The spar then builds up kinetic energy, and when it moves back upward, it pulls suddenly on the CWP. The kinetic energy of the spar is then absorbed by elongation in the CWP. This snap load may significantly overload the CWP.

Based on response in regular waves, the CWP is found to be sufficiently long and flexible so that significant snap loads do not occur. Secondly, the damping present in the system can greatly reduce any snapping that would occur.

The regular wave heave response of the spar is shown in Fig. 4-10, for two values of lower spring constant. For $K_L = 4360$, the lower spring constant of the CWP in compression is equal to the spring constant in tension, and the behavior is similar to a simple harmonic oscillator with a natural period of 7.6 seconds. For $K_L = 4.3$, which matches the CWP nonlinearity, the frequency response shifts into the higher periods.

Response in the 100-year storm is shown in Fig. 4-11, including maximum tension versus net buoyancy, for several values of damping, and minimum downward displacement versus net buoyancy. A net buoyancy of 6,000 K and a damping coefficient of slightly more than $10,000 \text{ K/(fps)}^2$ are selected for design. The mooring base design loads are 12,000 Kips for the vertical, and 1,500 Kips for the horizontal. Angular depictions at the CWP joints are given in Table 4-7.

The maximum tension in the CWP, assuming simultaneous maxima of inertial load and wave-induced force, 25,000 kips, is 13,000 kips higher than the vertical base load. The point below the buoyancy section must carry the suspended weight of the CWP. This value may be too high for the CWP design.

For several reasons, the applicability of the frequency domain computer programs written for CIRC CWP analysis may not be valid when applied to the spar-TAL. Frequency domain analysis is based on the assumption of linearity of response to wave height at each frequency. TAL heave is not a linear function of wave height because of the nonlinear stiffness. The response in heave for small waves is linear until the wave height is sufficient to cause the CWP to become slack. Not only will larger waves cause different response, but the frequency response characteristics will shift with heave amplitude as demonstrated in Fig. 4-10. Thus the theoretical basis of the programs is open to question with regard to spar heave, the most important mode of response for

Fig. 4-10 TAL Tension Response in Regular Waves

Fig. 4-11 TAL Response in Extreme Sea State

Table 4-7 MAXIMUM CWP ANGULAR DEFLECTIONS
IN EXTREME SEA STATES

Location	Angular Variation (deg)	Bottom of CWP Segment Number
CWP Joint	<u>+10</u>	1
CWP Joint	<u>+ 6</u>	2
CWP Joint	<u>+ 8</u>	3
CWP Joint	<u>+11</u>	4
Base Univ. Joint	<u>+20</u>	5

the spar-TAL. Secondly predicted CWP motions are based on small deflection amplitudes. Thus the transverse CWP damping is unlikely to be transferred into spar heave damping. Therefore the potentially most important mode of damping is not predicted in the frequency domain analysis, and the heave motions and tensions are overestimated.

To illustrate, a Paulling Program run was performed for IMODCO by Giannotti and Associates through Gibbs and Cox. A peak heave response is predicted at 7 sec, indicating that the spar is treated as a simple harmonic oscillator. The RMS value of CWP tension, 32,400 K, results in an approximate maximum CWP tension of $2,000 + (2)(32,400)(1.86)$, or 122,500 kips, considerably more than the selected design values.

4.2.3 Installation

It is assumed that the spar-CWP system is at the site and placed vertically with the CWP hanging from the spar. The basic TAL installation procedure is outlined as follows:

- o The gravity base is floated under its own buoyancy and towed to the site by a tug.

- o The gravity base is lowered to the seafloor by a crane. A series of slings is required, with each sling of a length equal to the vertical elevation lifting capacity of the crane barge. The base is lowered in a series of steps, with each step equal to the length of a sling. The top beam of each sling is supported on a structure projecting from the side of the barge, while carrying the base weight, in order that the next sling can be positioned.
- o When the base is nearly lowered to the seafloor, transponders on the base are used to position the barge until the base is over the desired location. The base is lowered the remaining distance until it rests on the seabed.
- o The slings and cables are relifted onto the crane barge.
- o The gravity base is filled with cement grout. Eight 3-in. ID grout hoses are lowered with the gravity base. These hoses are connected to a piping system in the base that distributes the grout evenly within the base. Grout is pumped from a grout mixer on board an installation barge. Since a large volume of grout is required, a workboat shuttle from a nearby land based cement plant or a storage facility is required. These workboats carry grout sacks which are continuously offloaded onto the installation barge. The grout mixture is formulated so that it can be mixed with seawater. The grout is pumped separately into each of the eight base compartments. The setting time is regulated so that the compartment is filled before the grout begins to harden. Television cameras lowered from the surface are used to monitor the grout installation and to determine when the compartments are filled.
- o The CWP and spar are maneuvered over the base and connected to a guide wire passing through the base socket. The spar is ballasted with water until the universal joint mechanical connector is pulled into place in the base. A mechanical manipulator or a diver in a pressure suit secures the mechanical connector by wedging the connector rams of the actuator screws used for that purpose.
- o The guide wire is then removed from the base, with a leader left in the guide tube for future CWP removal.

The retrieval of the spar/CWP requires no guide wires. The spar is ballasted until it submerges in the water, indicating that the uplift on the base is removed. The mechanical connector is unfastened by an unmanned submersible and the spar is floated free with the universal joint attached. The base is left in place.

4.2.4 Sensitivity to Requirements

The spar vertical elevation should be fixed within approximately 10 ft to prevent submergence of the elevated platform in the wave crests, and to prevent the discharge pipe modules from being exposed in the storm wave troughs. Ten ft represents an error of approximately 0.3 percent an extremely accurate value at these water depths. The water temperature gradient must be measured in order to compensate the hydroacoustic devices. CWP elongation is also considered when placing the base. Care is exercised in locating the gravity base, because it cannot be moved once it is in place. At a slope of 10 deg, the base must be placed within plus or minus 57 ft along the direction of slope of the seabed, to maintain a 10 ft vertical accuracy. The allowable error is greater along the bottom contour lines.

The precise reliability of the spar-TAL cannot be determined statistically, since none have been built. Some general statements can, however, be made about the system. The constant tension in the tension member amplifies the significance of any structural defects. Fatigue and corrosion fatigue require serious attention. The mode of failure of the mooring system could be dangerous. If 6,000 kip net buoyancy is present and the mooring system fails, the spar will rise suddenly. Once the system fails, there is no backup to prevent the Spar-TAL from drifting ashore and suffering great damage.

4.3 COST AND SCHEDULE

Tables 4-8 and 4-9 present capital cost estimates for the barge-MAL and the spar-TAL SKSS design concepts, respectively; late 1979 dollars are used throughout. The overall capital cost of the barge-MAL system is roughly 30 percent higher than that of the spar-TAL.

Table 4-8 MAL BARGE ACTIVE TENSIONING SKSS CAPITAL COSTS

	<u>1979 (\$K)</u>
MOORING SYSTEM COMPONENTS	
Swivel	150
Chain	5,885
Chain Stoppers	180
Fairleaders	1,520
Wire Rope	2,085
Anchors	470
Windlasses	6,720
Miscellaneous	<u>170</u>
Total Component Cost	17,180
Contingency, Home Office, Engineering, and Fees	<u>7,730</u>
Subtotal	24,910
MOORING SYSTEM DEPLOYMENT	
Installation Labor and Support Equipment	310
Deployment Barge Lease	875
Mobilization/Demobilization	<u>375</u>
Total Deployment Cost	1,560
Contingency, Home Office, Engineering and fees	<u>700</u>
Subtotal	<u>2,260</u>
OVERALL MOORING SYSTEM TOTAL	27,170

All individual component estimates shown for the MAL SKSS are direct from the actual or potential manufacturers; for those components not currently available, such as the windlasses, the costs shown represent the manufacturer's best ROM based on past experience. These manufacturers include: for windlasses, Western Gear Corporation, Luckert Manufacturing Company, Houston Systems Manufacturing Company, and Mitsubishi; for wire rope, British Ropes Limited, Fatzer AG, U.S. Steel Corporation, Elkem Spigerverket, and Thyssen; and for chain, Hamanaka International, Inc., and Ramnas. Windlass and chain costs each account for over one-third of total component costs, while fairleaders and wire rope are also important cost components,

Table 4-9 SPAR TAL SKSS CAPITAL COSTS

	<u>1979 (\$K)</u>
MOORING SYSTEM COMPONENTS	
Universal Joint	8,315
Pile Connector	1,700
Gravity Base	6,950
Total Component Cost	-
Contingency, Home Office, Engineering, and Fees	<u>(Included Above)</u>
Subtotal	16,965
MOORING SYSTEM DEPLOYMENT	
Installation Labor, Support Equipment, and Mobilization/Demobilization	4,165
Total Deployment Cost	-
Contingency, Home Office, Engineering, and Fees	<u>(Included Above)</u>
Subtotal	<u>4,265</u>
OVERALL MOORING SYSTEM TOTAL	21,230

each accounting for roughly 10 percent of component costs. As is seen later, wire rope costs are of greater importance to life cycle costs because wire rope is assumed to require replacement at least twice over the life of the OTEC plant.

The last entry in the component cost sector of the table covers a miscellany of special purpose links, shackles, and sockets. Mooring system deployment requires a specially equipped barge which is assumed to be available for lease at a rate of \$73,000/day. Should this barge have to be built to order for the specific purpose of OTEC SKSS deployment, its cost is estimated at approximately \$15,000,000. Labor costs are included in the deployment cost estimate at a rate of \$50/hr, and support craft (other than the deployment barge) are expected to cost roughly \$8,000/day.

To arrive at an overall estimate of SKSS capital costs, allowances are added to basic component and labor cost to cover costs associated with administrative and engineering activities, estimated at roughly 10 percent of basic costs, to provide for fees of approximately 10 percent, and to include a contingency buffer of some 20 percent of basic costs; it might be noted that transportation from the Gulf Coast to the operating site is included within this contingency, as component costs are given FOB Gulf Coast. Combining these three allowances multiplicatively, an overall combined allowance of some 45 percent is arrived at, and this is reflected in the allowances shown for these items in Table 4-8.

The TAL capital cost estimates include the following items:

Item 1. Universal Joint

- o Universal Joint Fabrication
- o Bushings
- o Miscellaneous Supply
- o Freight (West Coast to East Coast, Maryland)

Item 2. Pile Connector

- o Pile Connector Fabrication
- o Pile Connector Half Weld to Item 1
- o Freight (West Coast to East Coast, Maryland)

Item 3. Gravity Base

- o Gravity Base Fabrication
- o Pile Connector Half Weld to Item 3
- o Miscellaneous Supply
- o Installation Rigging Equipment

Item 4. Installation - Gravity Base

- o Equipment Mobilization/Demobilization
- o Gravity Base Tow to Site
- o Installation Prerigging

- o Gravity Base Installation
- o Ballast of Base by Concrete (50 x 10⁶ lb)

The following items are excluded from the TAL cost estimates:

Item 1. Universal Joint

- o Installation to OTEC CWP

Item 2. Gravity Base

- o Floating Bal/Debal Installation Tanks
- o Location Positioning Equipment
- o Location Positioning Marker Floats
- o Location Position Triggering Transponders
- o Seabed Leveling Grout
- o Sub-Base Location Template
- o Towing from East Coast to Pt. Tuna

Item 3. Installation - Gravity Base

- o Weather Downtime
- o Fuel Cost
- o OTEC CWP Stab-In into Gravity Base
- o Seabed Preparation
- o RCV Underwater Vehicles and Support Equipment
- o Seabed Cleanup

The dominant cost elements in the costs estimated for the TAL SKSS (Table 4-9) are the universal joint and the gravity base, which together account for some 90 percent of total component costs and 70 percent of total installed system costs. The overall installed cost of the Spar-TAL is some 30 percent lower than that of the barge-MAL. The costs associated with modification of the CWP required to accommodate the mooring loads are not included.

The life cycle costs (LCCs) associated with both SKSS designs are estimated according to the following rules:

- o The OTEC platform and SKSS are to start operation at the beginning of 1985 and have a 30-year operational life, thus ending operation at the end of 2014.
- o Capital cost expenditures take place at an even rate over the period from order placement to equipment delivery; thus, they are time-phased following the schedules presented in the next subsection.
- o Scrapping or disposal costs are assumed to be one-half of deployment costs, and to occur in 2015, the year following the end of operations.
- o Yearly local tax and marine insurance charges are expected to be roughly 3.5 percent of initial capital cost.
- o The yearly cost of inspection and routine maintenance of the platform is estimated at approximately 1 percent of initial capital cost.
- o All costs escalate at a yearly rate of 7 percent except for tax and insurance charges which remain fixed as a proportion of original (accounting) cost.

Table 4-10 shows the disbursement schedule and life cycle cost for the barge-MAL SKSS. The overall LCC is approximately \$45,000,000, some two-thirds higher than the capital cost. This reflects the inclusion in LCC of the costs of maintenance and eventual scrapping of the SKSS, taxes and insurance charges on it, and the cost of two replacements of the wire ropes, which are assumed to have a 10-year service life. The present cost of these two replacements is slightly over 10 percent of the total LCC. This high proportion of wire rope replacement cost in LCC is due partly to assuming that the cost of the operations involved in retrieving and disposing of old wire ropes, and replacing them with new ones, is approximately the same as the cost of the new ropes themselves. This assumed operational cost is almost certainly too high, as it is roughly equal to the cost of the original deployment operation; this high estimate was retained to introduce some conservativeness into the estimate. To test the sensitivity of LCC to this parameter, a separate calculation carried out for a 5-year wire rope life, results in a LCC increase

Table 4-10 BARGE-MAL LIFE CYCLE COSTS

	1983	1984	1985	1986	1987	1988	1989	1990
SWIVEL	0.	210.	0.	0.	0.	0.	0.	0.
CHAIN	0.	8254.	0.	0.	0.	0.	0.	0.
STOPPER	0.	252.	0.	0.	0.	0.	0.	0.
FAIRLEAD	0.	2132.	0.	0.	0.	0.	0.	0.
WIREROPE	0.	2924.	0.	0.	0.	0.	0.	0.
ANCHORS	0.	659.	0.	0.	0.	0.	0.	0.
WINDLASS	0.	9425.	0.	0.	0.	0.	0.	0.
MISC	0.	290.	0.	0.	0.	0.	0.	0.
CHDEF	0.	10842.	0.	0.	0.	0.	0.	0.
DEPLOYMENT	0.	3170.	0.	0.	0.	0.	0.	0.
SCRAP	0.	0.	0.	0.	0.	0.	0.	0.
SUBTOTAL	0.	38107.	0.	0.	0.	0.	0.	0.
TAX & INS	0.	0.	1334.	1334.	1334.	1334.	1334.	1334.
MAINT	0.	381.	408.	436.	467.	500.	534.	572.
TOTAL	0.	38488.	1742.	1770.	1801.	1833.	1868.	1906.

	1991	1992	1993	1994	1995	1996	1997	1998
SWIVEL	0.	0.	0.	0.	0.	0.	0.	0.
CHAIN	0.	0.	0.	0.	0.	0.	0.	0.
STOPPER	0.	0.	0.	0.	0.	0.	0.	0.
FAIRLEAD	0.	0.	0.	0.	0.	0.	0.	0.
WIREROPE	0.	0.	0.	11505.	0.	0.	0.	0.
ANCHORS	0.	0.	0.	0.	0.	0.	0.	0.
WINDLASS	0.	0.	0.	0.	0.	0.	0.	0.
MISC	0.	0.	0.	0.	0.	0.	0.	0.
CHDEF	0.	0.	0.	0.	0.	0.	0.	0.
DEPLOYMENT	0.	0.	0.	0.	0.	0.	0.	0.
SCRAP	0.	0.	0.	0.	0.	0.	0.	0.
SUBTOTAL	0.	0.	0.	11505.	0.	0.	0.	0.
TAX & INS	1334.	1334.	1334.	1334.	1634.	1634.	1634.	1634.
MAINT	612.	655.	701.	750.	802.	858.	918.	983.
TOTAL	1946.	1989.	2034.	13589.	2436.	2492.	2552.	2617.

Table 4-10 (Cont.)

	1999	2000	2001	2002	2003	2004	2005	2006
SWIVEL	0.	0.	0.	0.	0.	0.	0.	0.
CHAIN	0.	0.	0.	0.	0.	0.	0.	0.
STOPPER	0.	0.	0.	0.	0.	0.	0.	0.
FAIRLEAD	0.	0.	0.	0.	0.	0.	0.	0.
WIREROPE	0.	0.	0.	0.	0.	22632.	0.	0.
ANCHORS	0.	0.	0.	0.	0.	0.	0.	0.
WINDLASS	0.	0.	0.	0.	0.	0.	0.	0.
MISC	0.	0.	0.	0.	0.	0.	0.	0.
CHDEF	0.	0.	0.	0.	0.	0.	0.	0.
DEPLOYMENT	0.	0.	0.	0.	0.	0.	0.	0.
SCRAP	0.	0.	0.	0.	0.	0.	0.	0.
SUBTOTAL	0.	0.	0.	0.	0.	22632.	0.	0.
TAX & INS	1634.	1634.	1634.	1634.	1634.	1634.	2024.	2024.
MAINT	1051.	1125.	1204.	1288.	1378.	1475.	1578.	1688.
TOTAL	2685.	2759.	2838.	2922.	3012.	25741.	3601.	3712.

	2007	2008	2009	2010	2011	2012	2013	2014
SWIVEL	0.	0.	0.	0.	0.	0.	0.	0.
CHAIN	0.	0.	0.	0.	0.	0.	0.	0.
STOPPER	0.	0.	0.	0.	0.	0.	0.	0.
FAIRLEAD	0.	0.	0.	0.	0.	0.	0.	0.
WIREROPE	0.	0.	0.	0.	0.	0.	0.	0.
ANCHORS	0.	0.	0.	0.	0.	0.	0.	0.
WINDLASS	0.	0.	0.	0.	0.	0.	0.	0.
MISC	0.	0.	0.	0.	0.	0.	0.	0.
CHDEF	0.	0.	0.	0.	0.	0.	0.	0.
DEPLOYMENT	0.	0.	0.	0.	0.	0.	0.	0.
SCRAP	0.	0.	0.	0.	0.	0.	0.	82530.
SUBTOTAL	0.	0.	0.	0.	0.	0.	0.	82530.
TAX & INS	2024.	2024.	2024.	2024.	2024.	2024.	2024.	0.
MAINT	1806.	1933.	2068.	2213.	2363.	2534.	2711.	0.
TOTAL	3830.	3956.	4092.	4237.	4391.	4557.	4735.	82530.

LCC IN 1979 IN \$K: 44885.0

ASSUMPTIONS: .07 ESCALATION; .10 DISCOUNT RATE; .035 TAX AND INS

of roughly one-quarter, to approximately \$57,000,000. By contrast, assumption of a 10-day delay in deployment and scrapping operations, at a weather downtime rate of \$100,000/day (in 1979 dollars), only increases the total LCC by about 5 percent.

Table 4-11 shows the disbursement schedule and total life cycle cost for the spar-TAL SKSS. The overall LCC is approximately \$31,000,000, roughly one-half higher than the capital cost. It might be noted that no actual maintenance is planned for this system. The amounts shown under this heading are intended to cover the cost of periodic submarine inspection. Consideration of overall LCCs increases the apparent relative cost advantage of this concept over the barge-MAL SKSS as the latter's LCC exceeds that for the spar-TAL SKSS by some 50 percent. This increased advantage is primarily due to the lack of components requiring periodic replacement in the spar-TAL concept; all items in this design are expected to last out the 30-year operational life of the OTEC plant. In closing, it might be noted that TAL LCC is somewhat more sensitive to weather downtime than that of the previous system. A 10-day weather delay, costed now at the (appropriate) higher rate of \$250,000/day, results in an increase of over 20 percent on overall LCC.

Figures 4-12 and 4-13 depict, for the MAL and TAL SKSS designs, respectively, schedules for component order placement, SKSS integration and deployment, operations and recurring replacements, and eventual scrapping of the SKSS at the end of its useful life.

Table 4-11 SPAR-TAL LIFE CYCLE COSTS

	1983	1984	1985	1986	1987	1988	1989	1990
U-JOINT	0.	11662.	0.	0.	0.	0.	0.	0.
PILE CON	0.	2384.	0.	0.	0.	0.	0.	0.
GRAV BASE	0.	9748.	0.	0.	0.	0.	0.	0.
DEPLOYMENT	0.	5982.	0.	0.	0.	0.	0.	0.
SCRAP	0.	0.	0.	0.	0.	0.	0.	0.
SUBTOTAL	0.	29776.	0.	0.	0.	0.	0.	0.
TAX & INS	0.	0.	1042.	1042.	1042.	1042.	1042.	1042.
MAINT	0.	298.	319.	341.	365.	390.	418.	447.
TOTAL	0.	30074.	1361.	1383.	1407.	1432.	1460.	1489.

	1991	1992	1993	1994	1995	1996	1997	1998
U-JOINT	0.	0.	0.	0.	0.	0.	0.	0.
PILE CON	0.	0.	0.	0.	0.	0.	0.	0.
GRAV BASE	0.	0.	0.	0.	0.	0.	0.	0.
DEPLOYMENT	0.	0.	0.	0.	0.	0.	0.	0.
SCRAP	0.	0.	0.	0.	0.	0.	0.	0.
SUBTOTAL	0.	0.	0.	0.	0.	0.	0.	0.
TAX & INS	1042.	1042.	1042.	1042.	1042.	1042.	1042.	1042.
MAINT	478.	512.	547.	586.	627.	671.	718.	768.
TOTAL	1520.	1554.	1590.	1628.	1669.	1713.	1760.	1810.

	1999	2000	2001	2002	2003	2004	2005	2006
U-JOINT	0.	0.	0.	0.	0.	0.	0.	0.
PILE CON	0.	0.	0.	0.	0.	0.	0.	0.
GRAV BASE	0.	0.	0.	0.	0.	0.	0.	0.
DEPLOYMENT	0.	0.	0.	0.	0.	0.	0.	0.
SCRAP	0.	0.	0.	0.	0.	0.	0.	0.
SUBTOTAL	0.	0.	0.	0.	0.	0.	0.	0.
TAX & INS	1042.	1042.	1042.	1042.	1042.	1042.	1042.	1042.
MAINT	822.	879.	941.	1006.	1077.	1152.	1233.	1319.
TOTAL	1864.	1921.	1983.	2049.	2119.	2194.	2275.	2361.

	2007	2008	2009	2010	2011	2012	2013	2014
U-JOINT	0.	0.	0.	0.	0.	0.	0.	0.
PILE CON	0.	0.	0.	0.	0.	0.	0.	0.
GRAV BASE	0.	0.	0.	0.	0.	0.	0.	0.
DEPLOYMENT	0.	0.	0.	0.	0.	0.	0.	0.
SCRAP	0.	0.	0.	0.	0.	0.	0.	74202.
SUBTOTAL	0.	0.	0.	0.	0.	0.	0.	74202.
TAX & INS	1042.	1042.	1042.	1042.	1042.	1042.	1042.	0.
MAINT	1412.	1510.	1616.	1729.	1830.	1980.	2118.	0.
TOTAL	2454.	2553.	2658.	2771.	2892.	3022.	3161.	74202.

LOC IN 1979 IN \$K: 30998.0

ASSUMPTIONS : .07 ESCALATION; .10 DISCOUNT RATE; .035 TAX AND INS

Fig. 4-12 Ship-MAL Schedule

Fig. 4-13 Spar-TAL Schedule

Section 5

DEVELOPMENT AND TEST PROGRAM FOR SKSS

It is recommended that test activities be planned for accomplishment in three major categories. These consist of development testing early in the design program to confirm design assumptions, hardware tests for verification and evaluation of critical components of the proposed system; and finally full-scale exercises in the construction phase to check the functional integrity of selected system elements and to evaluate the techniques for deployment (Ref. 6).

5.1 SEAFLOOR SAMPLING AND PROFILING

Measurement of soil properties and the geologic structure of the ocean bottom at each of the eight anchor implantation sites is key to confirming the suitability of drag-embedment anchors. It is recommended that a site survey to define these characteristics be conducted before the next phase of SKSS design. Seismic surveying techniques are used to determine the sub-bottom profile. Soil depths of two to five times anchor height are required for drag embedment anchors. In the event that shallower depths are observed, then alternatives to the drag embedment anchor such as drilled and grouted pile anchors are required depending on the as-measured conditions. Alternatively, adjacent areas of the seafloor are surveyed for sites appropriate to drag embedment anchors. Core samples are required at each of the anchor locations to determine angle of internal friction, bearing capacity, density, shear strength, consistency, and sediment content. Data may be obtained using Doppler penetrometers at each location. In order to assess the potential fouling risk to the anchor legs and electrical riser system from sea floor obstructions, a side scan sonar survey of the area is also required. An assessment of the reduced data is required to determine suitability of drag embedment anchors, anchor set distance, and holding power.

5.2 SCALE MODEL TESTS

5.2.1 Multiple Anchor Leg

In order to evaluate response of the OTEC barge and SKSS in design sea states and modes of operation it is recommended that a 1/50th scale model of the barge be prepared and tested together with moorings which simulate the design and dynamic characteristics of the MAL SKSS. This test is recommended as a source of data for use in evaluating the critical design assumption of coupled barge-SKSS seaway response.

Data are obtained defining motions, excursion limits, and mooring leg tensions when the barge model is exposed to regular and random wave spectra. Of particular interest are dynamic excursion and anchor leg tension due to slowly varying wave drift force and moment. To this end long period wave groups are modeled which simulate likely occurrences at the site. Wave heights are varied up to a scaled Extreme Sea State with variable heading. Anchor leg loads are determined under conditions simulating active tensioning to verify that this technique optimizes tension loadings. This is accomplished by variation of anchor leg length in the conduct of the test program. Analysis of the data obtained is performed to confirm SKSS and barge response characteristics. In particular, long period mean tension and excursion are examined to assess the effects of slowly varying wave drift force and moment on the barge and SKSS.

Model testing is based on Froude scaling. With a model scale of 1:50, the barge includes a model of the CWP to a depth of approximately 60 percent of the maximum wave length or 10.5 ft in scale. Barge principal dimensions, weight, buoyancy, and mass moment of inertia, including the CWP, are modeled. A number of test basins which have the capability of modeling the desired environment are listed in Table 5-1.

5.2.2 Tension Anchor Leg

The loads on the mooring base are all that are required from the model tests for the design of the TAL-SKSS. Since the spar and CWP must be modeled correctly to reproduce the desired base loads and to provide verification of predictions, it is necessary to monitor the loads and response of the entire system. A design iteration of the CWP is recommended so that the Spar-TAL configuration is integrated prior to testing.

Model tests of most offshore structures are based on Froude scaling. The Reynolds numbers for wind and water motions are not modeled, but the resulting drag forces are approximately modeled correctly since the drag coefficients are fairly constant at the high turbulence ranges typically encountered.

The large water depth required for an OTEC plant limits the number of model test facilities that could test the Spar-TAL. A list of test basins and their maximum water depth is provided in Table 5-1.

The Spar-TAL system can be tested at OTC at a scale of 1/120. This is a smaller scale than usual for mooring systems. The 3,280-ft water depth scales to 27.33 ft, which allows extra freeboard in the 30-ft pit for waves.

Model tests could be conducted without the CWP by providing a set of vertical and horizontal springs to model the CWP axial stiffness and the buoyancy restoring force. This model would demonstrate the heave motions of the spar. The analysis, however, shows that damping is very important in limiting the spar heave resonance. The above simplified model does not provide a definitive value of damping and is therefore of little use in deriving design loads.

The mean wave drift force is measured at the base and is simply the mean horizontal base load. For tests without wind and current, this mean base load is equal to the mean wave drift force on the spar and CWP. The slowly varying

Table 5-1 TEST FACILITIES

Test Basin	Location	Maximum Depth (ft)
OTC	Escondido, CA	30
NSMB	Netherlands	18
SOGREAH	France	Approx. 9
NMI	England	25
Marine Dyn. & Ship Lab.	Ottawa, Canada	15
SSPA	Sweden	16.5
Hydronautics	Laurel, MD	35
Ship Research Institute	Mitaka, Tokyo, Japan	15

wave drift forces on the spar system cannot be measured by the proposed transducer arrangement. An entirely different model design is required, in which the long period drift motions would be restrained, thereby allowing measurement of the time-varying drift forces.

5.3 HARDWARE TESTS

Hardware testing is necessary for the wire rope section of the anchor leg. While wire rope is produced in sizes and load ratings larger than that required for the MAL SKSS, relatively little is known with respect to corrosion and fatigue life in long-term ocean deployment. In order to establish the wire rope service life, it is necessary to conduct an extensive testing program prior to the next phase of SKSS design. Combined testing is required to evaluate wire rope fatigue in seawater. In discussions with wire rope manufacturers it is clear that a cooperative, cost sharing venture is required for a program of this nature. For example, a program with Fatzer, A.G. would utilize existing facilities in Zurich, Switzerland, extensively involved in wire rope testing for aerial tramway systems. Availability of this facility and expertise provides a potentially lower cost effort than a similar program conducted in the United States.

Chain capacity to provide adequate fatigue and abrasion strength for a 30-year service life requires further investigation. Chain testing is required if adequate data is not available on performance of large diameter chain in deep ocean mooring. Tests exploring corrosion properties are conducted in seawater having chemical constituency, physical properties, and average temperature range which simulate those characteristics at the deployment site.

5.4 FULL-SCALE EXERCISES

A full-scale test is recommended to confirm that the tandem anchor assembly, consisting of the two 60,000-lb drag-embedment anchors and their connecting chain segment, can be set with proper orientation and embedment on the ocean bottom. This test, following the soils test and preceding detail design, also provides the opportunity to measure the lateral travel necessary for the assembly to achieve full embedment. This test provides data to both verify the concept of tandem anchors and to validate the techniques for predicting anchor set distance, essential to proper placement of the anchor assemblies during actual deployment at the operational site. As a secondary benefit, this test provides experience with which to refine the anchor deployment technique.

A deep water handling test is recommended to provide an opportunity, well in advance of OTEC mobilization, to evaluate the deployment system and its components. It also permits assessment of the procedures to accomplish this previously untried task. This test is conducted by the deployment contractor following completion of the OTEC SKSS deployment barge.

Estimated schedule and costs for each test are summarized in Table 2-1. All costs are stated in 1979 dollars.

Table 5-2 SUMMARY OF SKSS TESTING COSTS AND SCHEDULE

Test	ROM Cost (\$K)	Schedule (Days)
Seafloor Sampling and Profiling	125	15
Scale Model	40	7
Service Life Improvement Tests	128	730
Wire Rope Tests	100	270
Anchor Assembly	105	5
Deep Water Handling	220	6

Section 6

CONCLUSIONS AND RECOMMENDATIONS

The development of SKSS requirements, concepts, costing, evaluation and ranking is summarized. Preliminary designs are presented for two OTEC Stationkeeping Subsystems; the MAL with active tensioning for the barge and the spar TAL.

The stationkeeping performance requirements for the barge are satisfied by the MAL active tensioning SKSS. The MAL maintains station in the Extreme Sea State under conservative design loads and with loss of a windward leg. The system provides sufficient holding power to maintain station with the required excursion, is capable of altering leg lengths to effectively distribute loads, provides heading control of up to 90 deg, and is suitable for extrapolation to the commercial plant SKSS. MAL SKSS capital cost estimate is \$27.2 M, and life cycle cost is \$45 M. The MAL requires approximately two years from order of hardware to installation.

A development and testing program is recommended to provide confirmation of design assumptions, particularly design loads and seafloor geology, and hardware development, particularly wire rope service life, necessary for successful installation of the MAL in 1985. The MAL design is based on existing or minor extensions of manufactured components.

Active tensioning is shown to be an effective technique for reducing leg tension. The barge heading is controllable by lengthening all legs, thereby transferring tension to pendant lines. The extent of heading change, proportional to the extent of load sharing between pendant and chafing chains, is limited to 90 deg clockwise rotation. MAL cost sensitivity to watch circle is small as the Extreme Sea State requirement limits reduction in anchor leg scantlings.

A detailed deployment plan defines the steps and equipment required to install the MAL in the great depths at the Puerto Rico site. Procedures for inspection, maintenance and repair indicate the extensive operation required for wire rope replacement. Interfacing the MAL with the barge is shown to be noncritical, although large bending and heeling moments are induced in the barge by the SKSS. The potential interference between the CWP and a slack anchor leg in the Extreme Sea State, and between anchor legs and riser cables, requires further investigation to assess criticality.

The TAL is shown to potentially satisfy the SKSS design requirements for the spar platform. The design, based on extrapolation of existing SALMs, is sized to react loads which are significantly larger than the loads determined in conceptual design. Hence, the universal joint and gravity base structure are heavier and more costly than both the first concept and existing SALMs. The required service life is 10 years longer than present design requirements. The loads on the CWP, acting as an integral component of the SKSS, are determined. A CWP design iteration is required, particularly in the area of tension carrying capacity of the pipe joints. Extension of analytical models is required to adequately predict TAL performance in a seaway. The capital cost is \$21.2 M and life cycle cost is \$31 M.

TAL installation involves lowering the gravity base and grouting in place, followed by stab-in of the U-joint attached to the bottom of the CWP. This procedure, critically dependent on accurate measurement of water depth, is considered to be within the state-of-the-art in offshore engineering.

In comparing the MAL with the TAL, consider that the TAL is not appropriate to the barge while the MAL with modification is appropriate to the spar. A relative comparison is made in consideration of the choice of a SKSS for the spar.

<u>Factor</u>	<u>SKSS</u>
Installation	<u>MAL</u> is closer to SOA than TAL, considering depth and service life.
Electrical Riser	<u>TAL</u> provides more direct interface; less interference than MAL.
Failure	<u>MAL</u> has graceful mode of failure; TAL does not.
CWP Interface	<u>MAL</u> requires minimal interface with CWP; TAL major interface.
Platform Interface	<u>TAL</u> has minimal interface with platform; MAL has significant interface.
Life Cycle Cost	<u>TAL</u> has potential for lower life cycle cost.
Water Depth	<u>TAL</u> allows shallower site, thereby potentially lower costs in SKSS and ETS.
Risk-Criticality	<u>MAL</u> is found to have less risk than the TAL for the spar.
Schedule Risk	<u>MAL</u> has lower delivery risk because of fewer special fabrication items.
Deployment	<u>TAL</u> has lower economic risk as the high cost work barge needed for MAL deployment is not required for the TAL.

Design and analysis effort is recommended to further develop the two SKSS designs. MAL and TAL design refinement is recommended to reduce design costs and to conduct trades of SKSS requirements with other OTEC subsystems to assess the cost effectiveness of the prescribed performance requirements. Potential cost reductions may be found in reducing water depth and increasing watch circle. Additional areas for design cost reduction and which require development include:

- o For the MAL: wire rope sheathing and other corrosion inhibiting techniques, continuous pulling machines for chain, high efficiency drag embedment anchors for tandem configuration, fore and aft asymmetry of anchor legs, shorter anchor chain segment, verification of wave and fatigue loading predictions and development of empirical S-N curves for wire rope and chain.

- o For the TAL, lower cost alternatives to the U-joint, analytical model for prediction of spar-TAL response in a seaway, and CWP design iteration for TAL application.

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