DOE/NOAA/OTEC-5

PRELIMINARY DESIGNS FOR OCEAN THERMAL ENERGY CONVERSION (OTEC) STATIONKEEPING SUBSYSTEMS (SKSS)

Task I: Design Requirements. Final Report

June 1, 1979

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

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Ocean Systems
Sunnyvale, California

U.S. Department of Energy

Solar Energy

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PRELIMINARY DESIGNS FOR OCEAN THERMAL ENERGY CONVERSION (OTEC) STATIONKEEPING SUBSYSTEMS (SKSS)
TASK I: DESIGN REQUIREMENTS
FINAL REPORT

JUNE 1 1979

Prepared For

NATIONAL OCEANOGRAPHIC AND ATMOSPHERIC ADMINISTRATION
OFFICE OF OCEAN ENGINEERING
UNDER CONTRACT NA-79-SAC-00635

Prepared by

OCEAN SYSTEMS, LOCKHEED MISSILES & SPACE CO., INC.
With
IMODCO
SIMPLEX WIRE AND CABLE COMPANY
EAGER & ASSOCIATES

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FOREWORD

Lockheed Ocean Systems is performing the Preliminary Designs for OTEC Stationkeeping Subsystem (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. The SKSS design team includes 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 Task I - Design Requirements are presented in this report and in a briefing with NOAA/DOE personnel.

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Section 1
INTRODUCTION

Lockheed Ocean Systems is performing the Preliminary Designs for OTEC Stationkeeping Subsystems (SKSS) study contract for NOAA in support of the DOE OTEC program. Lockheed is supported by IMODCO, Simplex Wire and Cable Company, and Eager & Associates in this study. The results of Task I, Design Requirements, are presented in this report. The report consists of four sections - environment, requirements, assessment, and selection - each addressing a different aspect of SKSS design requirements and methodology to be followed in Task II, Concept Design.

Environmental conditions for the Punta Tuna, Puerto Rico site are reviewed and synthesized to provide definition of current, wind and wave severity, direction, and occurrence for service, operational, and extreme sea states (Section 2). SKSS performance requirements, including design life and watch circle, are followed by interface considerations particularly for the electrical transmission riser cable, and design criteria including safety and load factors (Section 3). The SKSS concepts will be analyzed to evaluate performance, reliability, and cost. Performance analysis conducted in Task I includes catenary anchor leg static calculations to size components, as well as drag due to environmental loads in the operational and extreme sea states for both ship and spar platforms. Dynamic analyses and trade studies to be conducted in Task II are presented (Section 4.1). A reliability and risk assessment analysis of the three basic SKSS types - single-, multiple-, and tension-anchor-leg moors - was completed, indicating that the multiple-anchor-leg/multiple-point rotary or turret moor has the lowest risk-criticality for the ship, while that for the spar is the multiple-anchor-leg/multiple-point moor. The catenary single-anchor-leg/single-point moor has insufficient reliability for both platforms (Section 4.2). The life cycle cost analysis methodology, including work breakdown structure, cost estimating, and cost minimization define the approach to costing to be followed throughout the study (Section 4.3). The results of these design trades and analyses will first be applied to concept ranking required for recommendation of a SKSS concept for each platform (Section 5).

Section 2
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 identification of a weather window. A compilation of results is presented in Table 2-1.

2.1 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 quality is variable and includes calcareous ooze ranging in grain size from clayey silt to silty mud underlain by dense sand, the latter indicative of a high-strength bottom. The Virgin Islands Basin is extremely flat and nearly devoid of local relief. An alternative to the slope site may be a site in this basin located 10 miles southeast of Punta Tuna in 6,000 ft of water.

2.2 CURRENT

Current data for the site are incomplete, particularly with regard to surface speed, speed and direction variation with depth, and seasonal variation. A current model is presented which reflects observations and predictions, including direction, surface current, and current profile.

Surface current is generally easterly or westerly following seafloor contour and daily tides. Measured flow direction to a depth of 200 meters is either 65 ± 35 deg, or 265 ± 25 deg, with equal probability of 0.5, and 240 ± 15 deg below 200 meters. Local wind-driven surface current is in the direction of and normal to wind direction.

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
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
Current Profile	See Fig. 2-2
Bottom Quality	Silt, Clay, Mud, underlain by dense sand
Bottom Slope (deg)	10 to 18
Operational Sea State:	
Maximum Wave Height (ft)	34.0
Significant Wave Height (ft)	18.9
Period of Maximum Energy (sec)	10.1
Wind (knots)	29.5
Surface Current (knots)	1.8
Seafloor Current (knots)	0.18
Current Profile	See Fig. 2-2
Astronomical Tide (Diurnal Range) (ft)	1.0
Astonomical Tide (Annual Max. Range) (ft)	1.8
Extreme Sea State:	
Maximum Wave Height (ft)	63.2
Significant Wave Height (ft)	35.1
Period of Maximum Energy (sec)	13.0
Wind (knots)	79.1
Surface Current (knots)	2.4
Seafloor Current (knots)	0.24
Current Profile	See Fig. 2-2
Astronomical Tide-Storm Surge (ft)	5.5
Seismicity:	
Occurrence	Frequent
Epicenters (depth - ft)	230,000 to 984,000

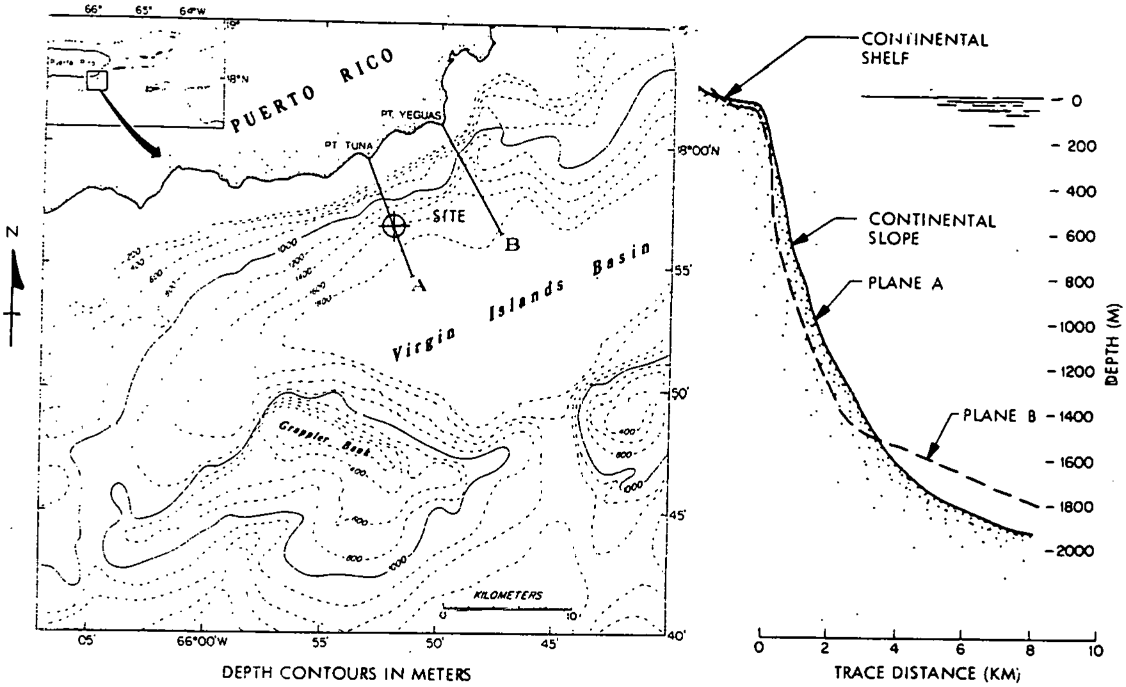


Fig. 2-1 Bathymetric Chart Showing Steep Slope at Punta Tuna (NOAA)

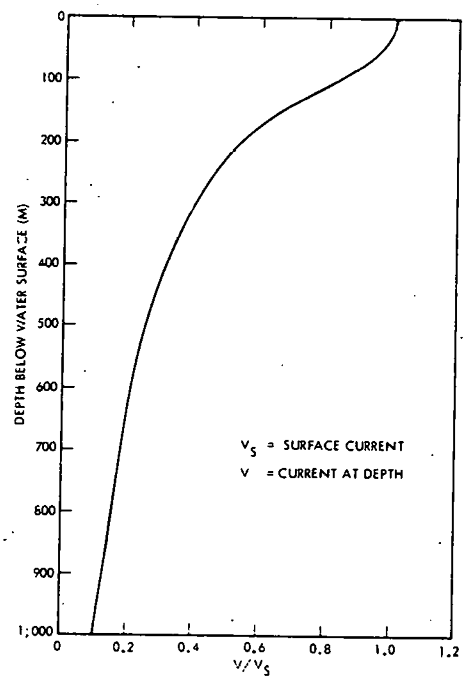


Fig. 2-2 Current Profile for Modular Experiment Plant Site in Puerto Rico (Ref. 2-2)

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, 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.

A wind-driven Ekman current is assumed to act in the direction of and normal to the hurricane path for the extreme sea state, with surface speed given by (Ref. 2-1):

$$V_s = 0.017\ V_{wind} \tag{2-1}$$

The total surface current for the extreme sea state with wind speed of 79.1 knots is 1.7 knots. These values are lower than 1.21 knots service and 2.76 knots extreme of Refs. 2-2 and 2-3.

In these references the normal surface current, V_{NS}, is the sum of geostrophic, 0.8 knot, and tidal flow, 0.4 knot, or 1.2 knots. To obtain the maximum surface current, the wind-driven current, V_{NS}, is added as follows:

$$V_{MAX} = \left(V_o^2 + \sqrt{2}\ V_o\ V_{NS} + V_{NS}^2\right)^{1/2}$$

with the angle of current to right of wind given by

$$\text{TAN}\ \theta_R = \frac{1}{1 + V_{NS}\sqrt{2}}\ /V_o$$

Thus, with

$$V_o = 0.023 \times 29.5 = 0.68$$

the surface current for the operational sea state is given by

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

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

This condition will be used for purposes of design per NOAA direction.

The current for the Extreme Sea State is obtained by this approach as

$$V_o = 0.017 \times 79.1 = 1.34 \text{ knots}$$

and

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

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

2.3 WIND

Synoptic meteorological observations provide data on wind frequency, magnitude, and direction for the general area in which Punta Tuna is situated (Ref. 2-4). Wind criteria for Service and Operational Sea States are derived from this source, while hurricane predictions provide criteria for the Extreme Sea State.

The direction from which the wind acts is easterly. A normal probability distribution function applied to observations yields the probability that the wind direction is bounded by θ_1 and θ_2 is

$$P\,(\theta_1 < \theta < \theta_2) = \text{erf}\left(\frac{\theta_1 - 70}{35}\right) - \text{erf}\left(\frac{\theta_2 - 70}{35}\right) \qquad (2\text{-}2)$$

where

θ = direction from which wind is acting, deg.
erf = error function

This function is assumed to be applicable to hurricane direction based on comparison with paths of tropical cyclones passing within 60 miles of Puerto Rico in an 88-year period.

Wind speed is derived as a function of significant wave height based on the sea state spectra of Ref. 2-2. Wind speed for Service and Operational Sea States is given by the following least squares fit to this data,

$$U = \exp\left[0.474 \ln 66.7 H_{1/3}\right] \tag{2-3}$$

where

U	=	wind speed, knots
$H_{1/3}$	=	significant wave height, ft

An estimate of wind speed associated with the Extreme Sea State based on the hurricane predictions of Ref. 2-2 is given by

$$U = 2 \exp\left[0.474 \ln 66.7 H_{1/3}\right] \tag{2-4}$$

2.4 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.

2.4.1 Wave Height

Meteorological observations of wave height occurrence in the ocean south of Puerto Rico provide cumulative probability distribution. Applying the method of Beard (Ref. 2-5) which assumes a Gaussian distribution, the following relationship is obtained for a given wave height:

$$T = \frac{1}{Fn} \tag{2-5}$$

where

- T = return period, or recurrence interval
- F = cumulative probability distribution function
- n = number of annual observations

A least squares fit to the observations (Ref. 2-2, Table 3-4) yields the following expressions for significant wave height for storms not exceeding 21 ft:

$$H_{1/3} = 1.897 \ln (1{,}662.24\ T) \tag{2-6}$$

where

- $H_{1/3}$ = significant wave height, ft
- T = return period, years

Standard error of this fit is 0.9 ft. A fit to the cumulative distribution function yields

$$H_{1/3} = 1.883 - 1.947 \ln (- \ln F) \tag{2-7}$$

where

- F = probability $(h \leqq H_{1/3})$
- h = wave height

Wave height for hurricane conditions is derived by fitting the Bretschneider hindcasts for the 50- and 100-year most probable hurricane hindcasts (Ref. 2-3). Thus, the following expression is assumed to be applicable for heights in excess of 21 ft:

$$H_{1/3} = 4.618 \ln 20T \qquad (2\text{-}8)$$

A comparison shows that for a 3-year return period the first expression (2-6) yields 16.2 ft and the second (2-8) 18.9 ft. A joint cumulative probability distribution function of the SSMO wave heights and hurricane hindcasts yields a value of 19.3 ft for 3-year return period (Ref. 2-6). The expression (2-8) is assumed to be applicable to shorter return periods of Service and Operational Sea States.

2.4.2 Wave Period

Wind-driven seaway spectra provide wave period correlated with wave height (Ref. 2-2, Section 7). These data are fit by a straight line on a log/log plot, yielding the following expression for modal period for wave heights of 21 ft and less:

$$T_o = \exp\left[0.507 \ln 5\, H_{1/3}\right] \qquad (2\text{-}9)$$

where

T_o = modal period, sec
$H_{1/3}$ = significant wave height, ft

Wave periods for hurricane conditions is given by the following expression based on the 100-year hindcast:

$$T_o = \exp\left[0.412 \ln 14.51\, H_{1/3}\right] \qquad (2\text{-}10)$$

This relationship will be utilized for Service and Operational sea state spectral modal periods as well as for Extreme sea state (Ref. 2-6).

2.4.3 Wave Direction

The directions from which sea and swell progress as given in Ref. 2-7 are combined and fit by the following expression for the probability that the direction will be bounded by θ_1 and θ_2

$$P\ (\theta_1 \leqq \theta \leqq \theta_2) = \operatorname{erf}\left(\frac{\theta_2 - 55}{47}\right) - \operatorname{erf}\left(\frac{\theta_1 - 55}{47}\right) \qquad (2\text{-}11)$$

where

θ = direction from which wave is progressing, deg

erf = the error function

The mean of 55 deg, or northeast, is less than the mean for wind direction, 70 deg. Wave direction in the hurricane condition is assumed to be equal to the hurricane track direction. A comparison of the distribution of storm wind direction with these tracks indicates that the hurricane wave direction is approximated by the wind distribution as given by Eq. (2-2), Section 2.3.

2.5 DESIGN SEA STATES

Environmental factors for design include three categories of sea states - service, operational, and extreme. The preceding synopsis of environmental conditions provide a basis for identification of wind, wave, and current magnitudes for design.

2.5.1 Service Sea States

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 frequency distribution (Table 2-2) provides duration of combined sea and swell wave height for each month. For the purpose of fatigue analysis, the Extreme Sea State loading will be included in the set of Service Sea States. With a specified value for significant wave height, Eqs. (2-1) through (2-11) provide wave period, direction and magnitude of wind, wave, and current for the service sea states.

2.5.2 Operation Sea State

This sea state is the highest wind, wave, and current condition for which the platform must remain operational in the required watch circle. The design

Table 2-2

WAVE HEIGHT FREQUENCY DISTRIBUTION

$H_{1/3}$ (ft)	(Hours/Month)										
	< 1	1-2	3-4	5-6	7	8-9	10-11	12	13-16	17-19	20-22
January	40	170	269	151	74	28	9	2	2	0	0
February	27	157	296	112	46	22	9	2	2	0	0
March	33	246	283	118	47	10	4	1	3	0	0
April	50	230	277	106	40	9	5	0	2	0	0
May	23	217	279	151	47	18	6	2	2	0	0
June	10	145	310	162	57	23	10	2	2	0	0
July	8	97	263	212	105	38	12	1	2	0	1
August	16	118	320	177	73	20	13	1	5	0	0
September	51	225	269	142	51	25	7	2	0	0	0
October	61	226	293	121	30	11	2	1	0	0	0
November	60	198	265	129	45	11	6	2	2	1	0
December	33	210	262	140	75	16	7	1	0	0	0
Annual	412	2,225	3,373	1,706	681	227	87	23	24	1	1
Cumulative	412	2,637	6,010	7,716	8,397	8,624	8,711	8,734	8,758	8,759	8,760

return period for this sea state is assigned a value of 3 years. The conditions for this sea state, derived from the preceding equations, are summarized in Table 2-1.

2.5.3 Extreme Sea State

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 as derived from Eqs. (2-1) through (2-11).

2.6 WEATHER WINDOWS

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 (hurricanes) 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. In this period the lowest occurrence and level of wind and wave are in December, the highest in January through March. 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 are identified as having the lowest frequency of occurrence of waves 5 ft and greater throughout the year.

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

2.7 REFERENCES

2.7.1 Cited References

The following references were cited by number in the text of Section 2.

2-1 Energy Research and Development Administration, Design Wave and Current Criteria for Potential OTEC Sites, by C. L. Bretschneider, 1977 ERDA Subprogram EA-03-04/57-70-91, May 1, 1978

2-2 Department of Energy, Environmental Data Package (Revised), Dec 12, 1978, Sections 3 and 7.

2-3 University of Hawaii, Hurricane Design Winds and Waves and Current Criteria for Potential OTEC Site: Punta Tuna, Puerto Rico, Dept. of Ocean Engineering Report 45-B, Apr 1979

2-4 U.S. Naval Weather Service Command, Summary of Synoptic Meteorological Observations, Vol. 4, Nov 1974

2-5 University of Hawaii, An Evaluation of Extreme Wave Climate at Keahole Point, Hawaii, by C. L. Bretschneider and R. E. Rocheleau, 1978

2-6 Communication, A. Pompa, 23 May 1979

2-7 University of Puerto Rico, Department of Marine Sciences, OTEC: Resource Assessment and Environmental Impact for Proposed Puerto Rico Site, Aug 1976

2.7.2 Uncited References

The following references, not specifically cited, were used in the preparation of Section 2.

University of Puerto Rico, Center for Energy and Environment Research, Current Measurements, Nov 25, 1978

Evans-Hamilton, Inc., The Meteorological and Oceanographic Conditions for Two Land-Based OTEC Sites, Sep 20, 1978

Naval Oceanographic Office, Oceanographic Cruise Summary Vieques Island, Puerto Rico Area, December 1968 to March 1969, IR No. 69-66, Aug 1969

-----, Oceanographic Cruise Summary Atlantic Fleet Tactical Underwater Range; Southeast Puerto Rico-1967, IR No. 67-76, Dec 1967

-----, Environmental Studies in Support of Atlantic Underwater Tactical Ranges, Report No. 0-15-66, May 1966

Section 3
STATIONKEEPING SUBSYSTEM REQUIREMENTS

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

3.1 PERFORMANCE REQUIREMENTS

The mooring system requirements are presented in terms of design environmental conditions, design criteria, performance and reliability assessment methodology, and design optimization methodology. The system requirements are significantly influenced by the mission defined for the OTEC Modular Experiments 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.

The design environmental conditions are summarized in Table 2-1. SKSS interface requirements are treated in Section 3.2 and design criteria are summarized in Section 3.2. Performance and reliability assessment methodology and design optimization methodology are presented in Sections 4 and 5, respectively. A performance specification, given in Appendix B, follows the format for OTEC subsystem specifications in use by LMSC.

Loading Analysis

The mooring system is subject to environment loads and installation forces. Environmental loads imposed on the system to be considered are wave, wind, current, and earthquake loads. Installation forces on the mooring system include lifting, loadout, launching, and uprighting forces. A performance simulation of the mooring system will be performed by computer analyses and other analytical methods. Performance characteristics that will be analyzed are watch circle excursions, tensions in mooring components, stationkeeping ability, and component stresses.

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 interfaces lead to significant system design requirements.

3.2.1 Platforms

The mooring system is required to position two different ocean platforms - the ship type and spar. The characteristics of the ship type and spar platforms are given in Tables 3-1 through 3-3.

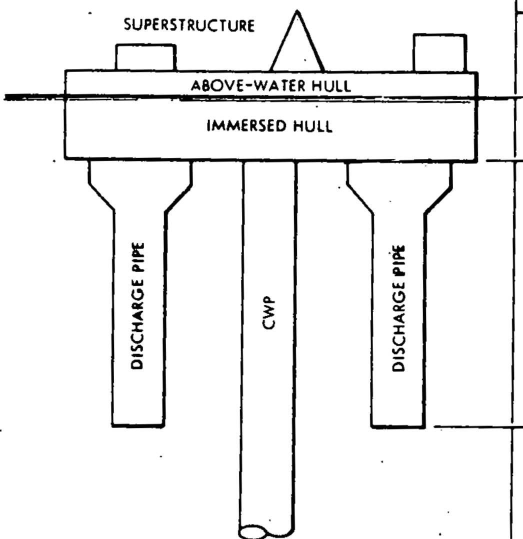
Table 3-1

SHIP TYPE AND SPAR CHARACTERISTICS

Characteristics	Ship Type	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 (lt)	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

Table 3-2

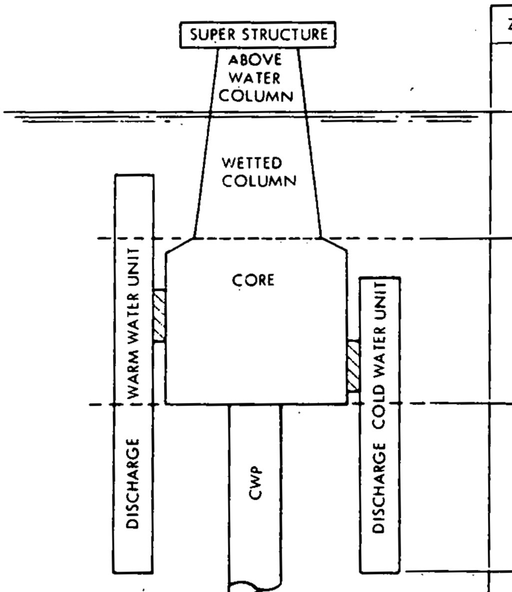
PLANTSHIP PROJECTED AREAS AND DRAG COEFFICIENTS



Z (ft)	COMPONENT	AREA (ft^2) HEAD	AREA (ft^2) BEAM	C_D
	WIND	7,460	13,434	0.8
0	CURRENT	7,665	24,770	0.6
	WAVE DRIFT	–	–	0.5 TO 0.9
65				
	CWP CURRENT	88,050	88,050	0.3 TO 1.2
330				
3000				

Table 3-3

SPAR PROJECTED AREAS AND DRAG COEFFICIENTS



Z (ft)	COMPONENT	AREA (ft^2)	C_D
	WIND	4,425	0.6
0			
60			
	CURRENT	40,480	0.6
	WAVE DRIFT	–	1.0
215			
	CWP CURRENT	83,550	0.3 TO 1.2
330			
3000			

Parameters which influence horizontal forces and yaw moment on the platform include length-to-beam and length-to-draft ratios, projected wetted and windage areas, and draft. Ship heading influences drag forces on the mooring system, platform and cold water pipe stresses, and platform flow separation characteristics.

Other interface requirements include space to lead-in lines; down force on hull and spar; material compatibility between mooring lines, winches, and fittings; the remaining ocean systems; and power system.

3.2.2 Electrical Transmission System

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

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

wherein operation is defined as the transmission of electrical power via the riser cable and submarine cable to the grid on Puerto Rico.

Cable attachment is not required beyond the Design Operational Sea State. However, criteria for suspension of operation which are influenced by mooring system performance characteristics include maximum tolerable amplitudes of:

- Stress in the riser cable
- Stress in the mooring lines
- Off-station excursions
- Platform motion
- Platform heading
- Stress in cold water pipe
- Cable/mooring-leg relative excursions

The watch circle requirements are:

- o Average water depth: 4,000 ft
- o Watch circle radius: 400 ft
- o Return period of design storm: 3 years

The first aim of watch circle limitation is to limit tensions in the riser cables to levels at which both static and dynamic loads can be tolerated by the strength components and cable insulation. Exceedance of nominal watch circle during unusual storm conditions may contribute both higher than normal base tension in the riser cable and higher than normal dynamic forces due to wave action associated with the storm. This combination presents potential risk of fatigue failure. Therefore, it is necessary at this time to limit the duration of watch circle exceedance to a few hours (say 3 hours). Design of cable system dimensions can probably accommodate a watch circle radius of up to 800 ft for these durations. A systems interface study is underway which includes design iterations between the mooring and riser cable systems. This approach will lead to identification of an optimum, integrated mooring system, designed to maximize operability at minimum life-cycle system cost.

In addition to the limitations due to tension and fatigue loading, 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 cold water pipe must be avoided to preclude physical damage to the cable.

Riser cable twist and torque considerations will be addressed. 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. If the cables are attached to a portion of the plant that is allowed to rotate, 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 mooring legs. Additional background on the ETS-SKSS interface is provided in Appendix A.

3.2.3 Cold Water Pipe

The SKSS-CWP interface is particularly significant in the tension-anchor-leg/monopod concepts. The material for the tensioned anchor leg (TAL) cold water pipe is concrete. The CWP is 30 ft in diameter and is 3,000 ft long. The horizontal wave force exerted on the cylindrical cold water pipe is related to the instantaneous components of water-particle velocity and acceleration in the direction of wave propagation. The wave force consists of two components - the drag force, which is due to the horizontal particle velocity, and the inertial force, which is related to the acceleration of the water particle.

Wave-induced vibrations are to be included in the design, with the goal to avoid resonance between wave and structural frequencies. The criterion involved when checking frequencies is to be sure that the frequency of the stationkeeping subsystem is not in the wave spectrum or vortex shedding range.

Vortices are shed in the wake of the cold water pipe in the wave-induced flow past the pipe. Vortex shedding occurs at a frequency, Fv, that is a function of free-stream velocity, Vn, and the pipe diameter, D. This frequency is directly affected by the Strouhal number, S, a function of the Reynolds number.

3.3 CRITERIA FOR DESIGN

The standards used in the design of the stationkeeping system are:

ABS	Rules for Building and Classing Single Point Moorings
ABS	Rules for Building and Classing Steel Vessels

API-RP2A	Recommended Practice for Planning, Designing, and Constructing Fixed Offshore Platforms
AISC	Steel Construction Manual
AWS D1.1	American Welding Society Structural Welding Code
ASME	Section VIII Boiler and Pressure Vessel Code
AWS A2.0	American Welding Society Standard Welding Symbols
ASTM	American Society for Testing and Materials - Specifications
ANSI B31.4	Liquid Petroleum Transportation Piping Systems
API Std 1104	Standard for Welding Pipelines and Related Facilities
SSPC	Surface Preparation Specifications
NEC	National Electrical Code

The application of these standards along with appropriate safety factors for individual components leads to the criteria summarized in Table 3-4. These basic design criteria are in terms of system design criteria, component technology design criteria, and deployment and operational criteria. Variations from these standards are to be based on sound engineering principles and are subject to review of the approval agencies.

Table 3-4

SUMMARY OF SKSS BASIC DESIGN CRITERIA

SYSTEM DESIGN CRITERIA
Fabrication and Cost Effectiveness
Implant and Recovery Effectiveness o Procedures o Problems
Performance o Predictability o Confidence Level
Ability to Scale to Commercial Plant Size
Effective Mooring System Stiffness o Planar o Torsional
Sensitivity To Design Sea States

Table 3-4 (Cont.)

COMPONENT TECHNOLOGY DESIGN CRITERIA

Load Comparison Computer Programs
- o Static
- o Dynamic

Anchor Technology Criteria
- o Gravity (deadweight)
- o Pile
- o Drag embedment

Loading Criteria and Safety Factors
- o Anchor Pullout Safety Factor $\left(\frac{\text{Wet Weight of Anchor}}{\text{Vertical Force Component}}\right)$(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 - $\frac{\text{Anchor Holding Power}}{\text{Horiz. Force Comp. For 1/3 Line Breaking Strength}} \geqq 2$
- o Maximum Operating - $\frac{\text{Anchor Holding Power}}{\text{Horiz. Force Comp. for 1/2 Line Breaking Strength}} = 2$
- 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

$\frac{\text{Hawser Load (SPM Through Different Faileads - Max. of 2)}}{\text{Number of Separated Mooring Lines}} \geqq$ 40% Break. Str.

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

Mooring System Stiffness	Maximum Tension/ Breaking Strength	Excursion, % Depth
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

Table 3-4 (Cont.)

Allowable Structural Stress Levels

- Gravity and Mooring Loading:
  - 60% of yield strength for tensile stresses
  - 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
- 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
- Compressive Stresses from Combined Axial and Bending Loadings

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

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

- Column Buckling Stresses:

  Elastic Buckling Stress

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

F_e = elastic buckling stress

F_y = yield stress

E = modulus of elasticity

Table 3-4 (Cont.)

L = column length

r = least radius of gyration

K = an effective length factor to be determined as per the latest AISC code

o Critical Buckling Stress of a Column:

$$\bar{F}_c = F_y - (F_y^2/4\pi^2 E)(KL/r)^2$$

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

Pile and Pile Foundation

o $\dfrac{\text{Ultimate Soil Capacities}}{\text{Allowable Soil Capacities}} = 2$

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/ft^2)

A_s = side surface area of pile (ft^2)

q = unit end bearing capacity (lb/ft^2)

A_p = gross end area of pile (ft^2)

qA_p = capacity of internal plug

o Load to Foundation Safety Factor = 2

o Maximum Pile Deflection ≦ 1/10 Pile Diameter

Table 3-4 (Cont.)

Miscellaneous Design Considerations

- o Rotational Restraint - Yaw ≦ 90 deg
- o Ductility
- o Abrasion, Wear, Scour
- o Biofouling
- o Corrosion
- o Auxiliary Mooring Equipment
- o Winch and Tensioner
  - Reliability
  - Maintenance
- o Fatigue

DEPLOYMENT AND OPERATIONAL CRITERIA

Weather Window Requirements

- o Deployment
  - Transportation
  - Anchor Lowering
  - Line Layout
  - Pretensioning
  - Inspection
- o Maintenance/Inspection
  - Regular
  - Semi annual
  - Annual
- o Special Periodic Survey

Cost Effectiveness

- o Fabrication
- o Implantation
- o Inspection

Table 3-4 (Cont.)

o Maintenance o Repair o Replacement o Recovery
Reliability of: o Implant o Recovery

Section 4
DESIGN ASSESSMENT

SKSS concepts will be analyzed to evaluate performance, reliability, and cost. This approach to design assessment is described in this section, including results of preliminary loads analysis and reliability assessment. Additional analysis will be conducted in Task II for design ranking and selection, and in Task III, Preliminary Design.

4.1 PERFORMANCE ANALYSIS

Mooring performance assessment will be conducted using computer analysis and other analytical methods. Performance characteristics to be studied are watch circle excursions, tensions in mooring components, stationkeeping ability, and component stresses.

Mooring system candidate concepts fit into three configuration categories. These are the single-anchor-leg (SAL) with single-point mooring (SPM), the multiple-anchor-leg (MAL) with single and multiple-anchor-leg moorings (MALM), and the tensioned-anchor-leg (TAL) mooring. From these three categories, eight concepts are being considered. Figure 4-1 illustrates these three categories and the eight concepts. The approach to performance analyses of these mooring systems will be based in part on the techniques of Ref. 4-1 through 4-9. Performance analyses will consist of static loads, dynamic loads, and trade studies.

4.1.1 Static Loads

Preliminary mooring system performance characteristics were examined to illustrate the approach. The system is a catenary, multiple-anchor-leg of wire rope and chain. The method used is applicable to the design of mooring lines for deep water applications wherein the dimensionless form of the

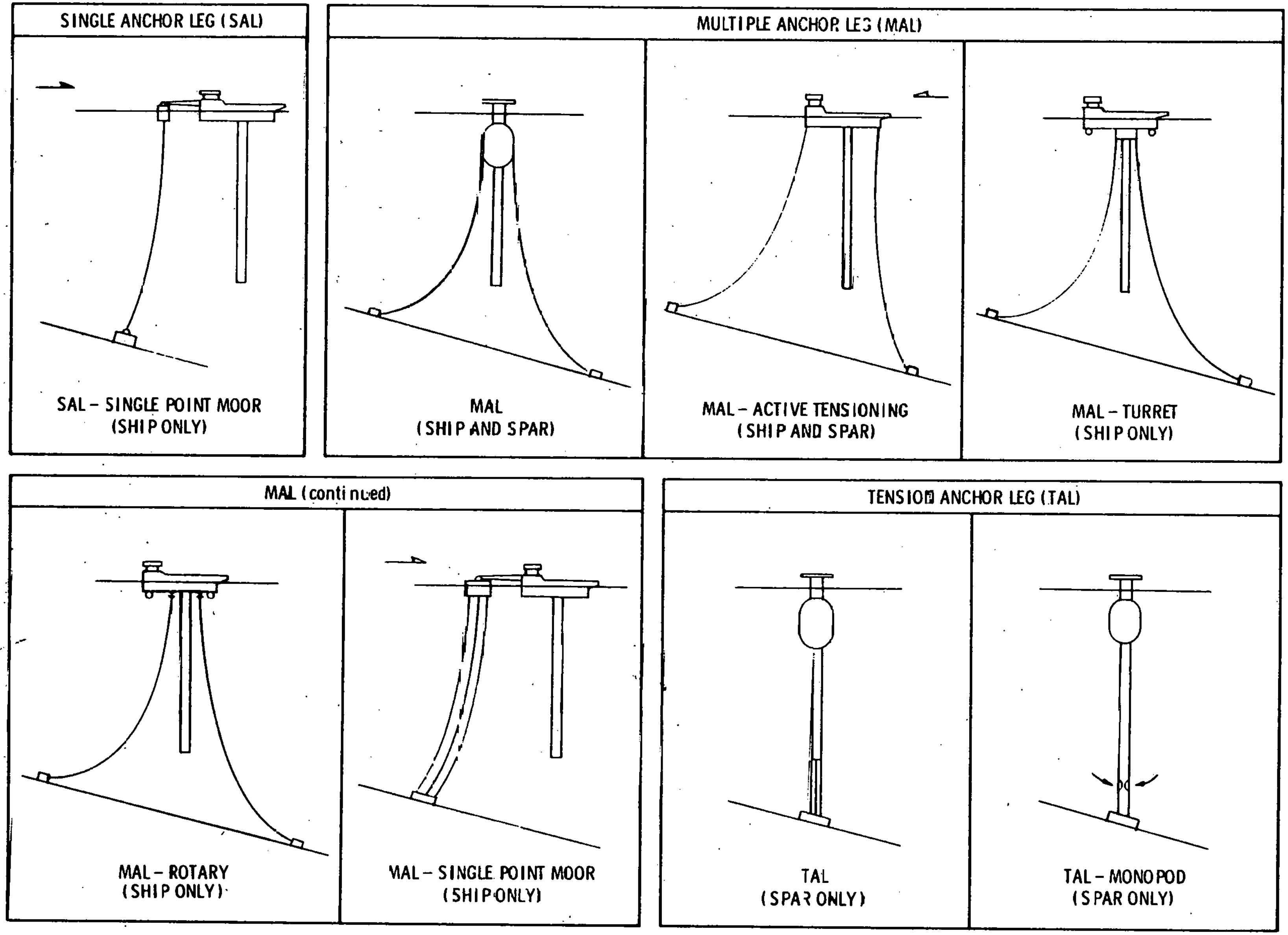


Fig. 4-1 Three Categories and Eight Concepts for SKSS

catenary equations for multiple component mooring lines are employed. The catenary equations are nondimensionalized by scaling length with respect to D, the depth of the water, and forces by DW_n, where W_n is the net weight per unit length. Figure 4-2 illustrates the multiple component mooring line dimensional and dimensionless variables. Figure 4-3 further illustrates a typical rope-chain mooring line in the pretension and excursion configurations.

A 3-in.-diameter wire rope was selected with a breaking strength of 1,045 kips weighing 16.9 lb/ft in combination with 3-1/16-in.-diameter chain with a breaking strength of 1,086 kips weighing 80.7 lb/ft. A water depth of 4,000 ft was assumed while an excursion of 10 percent of water depth was the design goal for this preliminary analysis.

The results of the analysis are summarized in Table 4-1. Cable tension of 20 percent of its breaking strength is realized for pretensioning. These and other key performance characteristics provide insights to viable trade studies. A summary of the environmental loading for the ship and spar is presented in Tables 4-2 and 4-3. Specific excursions, pretension, and restoring force criteria will be iterated to obtain the desired stiffness to satisfy the environmental loading for the ship and spar. Further refinements to include clump weights and multiple anchors, as well as line extensibility, are viable design considerations.

4.1.2 Dynamic Loads

The mooring system is subject to environmental and installation loading. Environmental loads to be considered are wave, wind, current, and earthquake loads. Installation forces on the mooring system include lifting, loadout, launching, and uprighting forces.

Table 4-1

MOORING LINE LOADS AND EXCURSIONS
(FROM PRELIMINARY PERFORMANCE ANALYSIS)

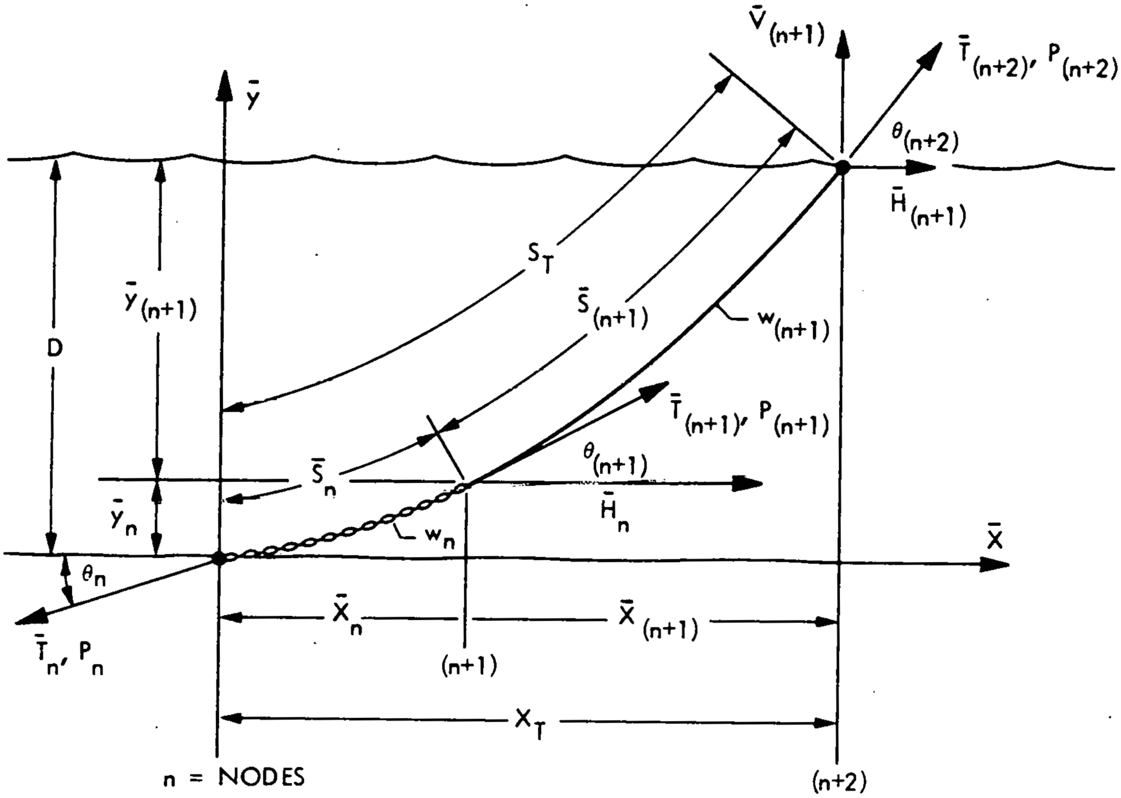
Percent of Breaking Strength	Cable Tension	Horizontal Load	Vertical Load	Top Angle θ^o (n+2)
20[a]	215 kips[a]	136 kips[a]	166 kips[a]	50.7[a]
25	261 kips	176 kips	193 kips	47.7
33	348 kips	252 kips	240 kips	43.5
50	523 kips	411 kips	322 kips	38.0

(a) Pretension Values

EXCURSION

$$d = (X_T - X_{T_o}) - (S_T - S_{T_o})$$

Percent of Breaking Strength	X_T (ft)	S_T (ft)	d (ft)	Percent of Depth
20	5,400	6,840	0	0
25	5,758	7,135	63	1.6
33	6,439	7,711	168	4.2
50	7,649	8,716	373	9.3



WHERE

$w_{(n+1)}$	=	WIRE ROPE WEIGHT PER FOOT
w_n	=	CHAIN WEIGHT PER FOOT
$S_{(n+1)}$	=	WIRE ROPE LENGTH
S_n	=	CHAIN LENGTH
$T_{(n+2)}$	=	MOORING LINE TENSION AT TOP
$P_{(n+2)}$	=	SLOPE OF MOORING LINE AT TOP
$V_{(n+1)}$	=	MOORING LINE VERTICAL LOAD AT TOP
$H_{(n+1)}$	=	MOORING LINE HORIZONTAL LOAD AT TOP
D	=	DEPTH OF MOOR
X_T	=	HORIZONTAL PROJECTION OF MOORING LINE

NOTE: QUANTITIES ARE NONDIMENSIONALIZED BY D, DEPTH OF WATER AND BY W x D.

Fig. 4-2 Multiple-Component Mooring Line

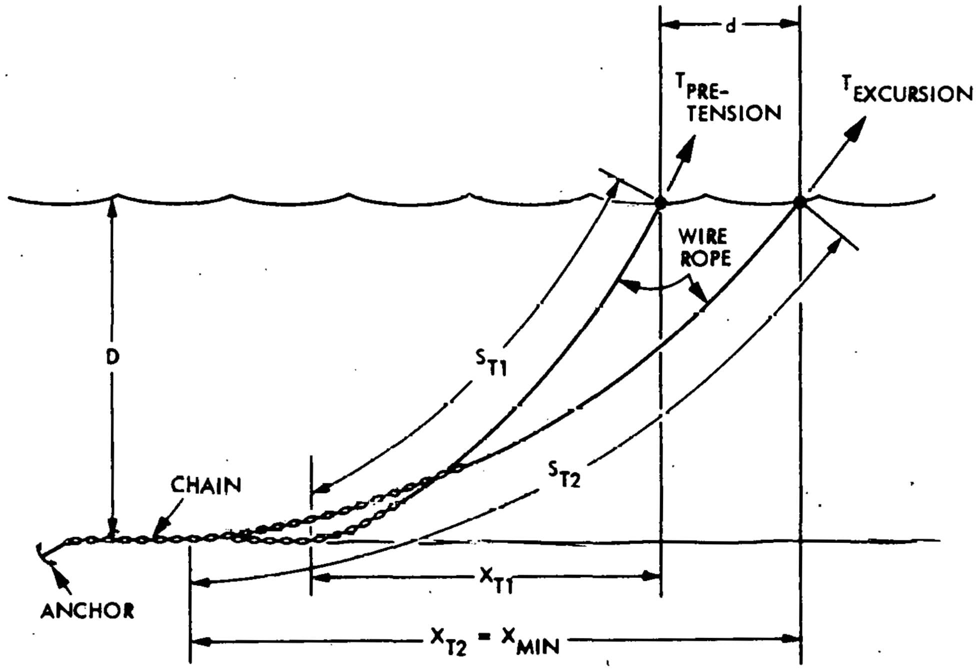


Fig. 4-3 Typical Rope Chain Anchor Leg on Station and at Excursion Condition

Waves exert dynamic loading on the moor and platform. The portion of wave energy which must be absorbed by the mooring system is dependent in part on the moor stiffness and platform fixity in the moor. The Tension-Anchor-Leg Mooring computer program will be used to analyze the wave energy force. Wave-induced vibrations of the moor platform will be considered particularly for the tensioned-anchor-leg moor. The natural frequencies of the moor will be well separated from the wave peak energy frequency and vortex shedding frequency. Dynamic simulations using the TOWER program will be conducted as appropriate for the SAL and TAL moors.

The steady drift force due to waves is proportional to the square of wave height. It is a nonlinear force with components both independent of time and dependent on higher wave frequency harmonics. An approximate relationship is used to estimate the wave drift force on the platforms in a narrow-band, irregular sea. Drift force coefficients applicable to the spar as derived from second-order potential theory or by model tests of the spar in waves are not available. Appropriate coefficients for both platforms will be pursued in Task II.

The influence of platform heading on the mooring system is examined in terms of the dependence of platform response on wind, wave, current, and heading. The spar is axisymmetric and is assumed to have no preferred orientation. Ship response to sea state, however, is dependent on heading.

Tables 4-2 and 4-3 summarize the estimated wind, wave, and current static and quasi-static loads on the ship and spar. Both operational and extreme sea state conditions are summarized, including ship response to heading, for this coplanar loading case. Yawing moments will be computed for headings other than beam and head. Additional wave drift force estimates will be prepared.

Holding power is the mooring capacity to react imposed loads, and it is reasonable to expect that holding power will decline with time. Cyclic loads, corrosion, abrasion of lines and components, shift in soil, and soil saturation will all contribute to this incremental loss in holding power. One source of cyclic loading, for example, is line strumming due to shedding of vortices formed by ambient current and/or line oscillations. Such life-cycle loads comprise the set of loads to be examined for service sea state conditions.

Installation lifting, loadout, launching, and uprighting forces while moving the components of the SKSS from the fabrication site to the offshore location requires that dynamic as well as static loadings be analyzed. Loadout forces occurring during transportation are determined considering the height, length, and period of waves encountered during tow. Launching and uprighting forces are dependent on how the structure arrives at the offshore site, whether horizontal on the barge, in the water, or in a vertical tow position. Forces in this stage of installation occur mainly from lifting and submergence pressures.

Table 4-2

SUMMARY OF ENVIRONMENTAL LOADING - SHIP[a]

Loading	Operational Sea State			Extreme Sea State		
	F_X(lb)	F_Y(lb)	N (ft-lb)	F_X(lb)	F_Y(lb)	N (ft-lb)
Head (B_1 = 90 deg)						
Wind	-20,312	0	0	-146,094	0	0
Current						
Hull	-43,183	0	0	-76,770	0	0
CWP	-59,661	0	0	-112,231	0	0
Discharge Pipes	-81,671	0	0	-145,193	0	0
Wave Drift	-133,375	0	0	-104,785	0	0
TOTAL	-338,202	0	0	-585,073	0	0
Beam (B_1 = 0)						
Wind	1,107	-31,705	0	7,959	-228,079	0
Current						
Hull	0	-135,975	0	0	-241,733	0
CWP	0	-59,661	0	0	-112,231	0
Discharge Pipes	0	-81,671	0	0	-145,193	0
Wave Drift	0	-420,517	0	0	-330,376	0
TOTAL	1,107	-729,529	0	7,959	-1,202,843	0

(a) Wind, wave, current coplanar toward west

Table 4-3

SUMMARY OF ENVIRONMENTAL LOADING - SPAR[a]

Loading	Operational Sea State			Extreme Sea State		
	F_X(lb)	F_Y(lb)	N(ft-lb)	F_X(lb)	F_Y(lb)	N (ft-lb)
Wind	-10,837	0	0	- 77,914	0	0
Current						
Core	- 9,854	0	0	- 79,103	0	0
CWP	-43,418	0	0	- 81,360	0	0
Wave Drift	-49,819	0	0	-171,824	0	0
TOTAL	-113,928			-410,201		

(a) Wind, wave, current coplanar toward west.

4.1.3 Trade Studies

A sound technical approach depends on trade studies to establish the design path early in the project. A decision in any one of the trades will have across-the-board impact on all the others. The best combination requires several iterations of the tradeoff process, beginning with an initial screening to narrow the field of candidates. This is followed by a quantitative evaluation of relative performance and cost, supported by engineering analysis. The significant trade studies to be conducted are summarized in Table 4-4.

Table 4-4

TRADE STUDIES

1.	Wire-Rope-Length/Chain-Length Ratios (at 4,000-ft depth)	vs.	Excursion. Restoring Force. Pretensioning. Cost.
2.	Holding Power (in sand, clay, mud)	vs.	Deadweight Anchor. Drag Embedment. Pile Group Anchor.
3.	Anchor Types (bar graph)	vs.	Cost (including engineering, fabrication, transportation to site, and lowering)
4.	All Wire Rope System (diameter variations at 4,000 ft)	vs.	Excursion. Restoring Force. Pretensioning. Cost.
5.	Single Leg Moor (pros and cons)	vs.	Multiple Leg Moor
6.	Anchor Types	vs.	Weather Window Requirements
7.	Anchor Selection (rating-table form)	vs.	Compliant to Sand, Mud, Clay. Ship and Equipment Support. Ease of Transport to Site. Fabrication to State-of-the-Art. Compliant to Seafloor Variation. Cost. Developmental Complexity Implant Sensitivity to Depth. Resistance to Vertical Loading. Resistance to Horizontal Loading. Omnidirectional Stability.
8.	Mooring Line Selection (rating-table form) All Wire Rope All Chain W.R./Chain Combination Synthetics	vs.	Effectiveness at 4,000 ft. Weight Effectiveness. Available Restoring Force. Pretension Value Range. Abrasive Resistance. Fabrication to State-of-the-Art. Excursion Range. Cost.

Table 4-4 (Cont.)

9.	Mooring Concept Selection (rating-table form) SAL-SPM MAL MAL-Turret MAL-Rotary MAL-SPM TAL TAL-Monopod MAL-Active Tensioning	vs.	Developmental Extension to State-of-the-Art. CWP/Platform (interface stresses). Excursion Flexibility. Cost. Engineering Design Effort. Anchor Technological Development. Elec. Trans. Cable Design. Weathering. Rotational Restraint. CWP Bending Moment. Winch and Tensioner Design. Implant Support Services. Recovery Cost.
10.	Alternative Mooring Sites off Pt. Tuna	vs.	Depth of Moor. Bottom Profile Evaluation. Relative Mooring Cost Factor. Deployment Considerations. Bottom Composition Merits.

4.2 RELIABILITY AND RISK ASSESSMENT

4.2.1 Summary

The eight Stationkeeping Subsystem concepts were 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 spar hulls the ranked concepts are:

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

Discrimination could not be made between the turret and rotary versions of the ship moors nor 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 susceptable to entanglement in its slack condition.

Although the OTEC SKSS will be subjected to some exceptionally severe conditions, acceptable reliability can be achieved. A highly disciplined development program will be required. This program must carefully utilize all major risk-reduction opportunities as outlined in this section.

4.2.2 Methodology

For purposes of this report, 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 predicts the relative, adverse impact upon the OTEC Demonstration Program, resulting from that failure mode.

Risk factors have been necessarily deduced, based upon extensive ocean engineering and operating experience. Absolute reliability values could be obtained only after 30 years of operating experience with a statistically significant number of moors that represent each of the concepts. Certain of the concepts and several of the conditions to be imposed upon the OTEC SKSS differ greatly from the existing operating experience. Therefore, reliability predictions could not be justifiably obtained from a synthesis of component reliability values.

The relative risk and failure criticality factors for each concept have been 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 can be obtained.

The eight mooring concepts are categorized into three basic concepts for purposes of risk and criticality assessments. These basic concepts are the single-point moor (SPM), the multiple-point moor (MPM), and the tension-anchor-leg moor (TAL). The remaining concepts were analyzed and assessed as variations of these three basic concepts.

The failure modes, which are potentially operative in one or more of the concepts, were deduced utilizing the scaled drawings of Figs. 4-4, 4-5, and 4-6. The conditions which produce significant risk of failure in one or more of the concepts were derived, opportunities available to compensate for the risk conditions were identified, and the determinants of failure criticality were defined.

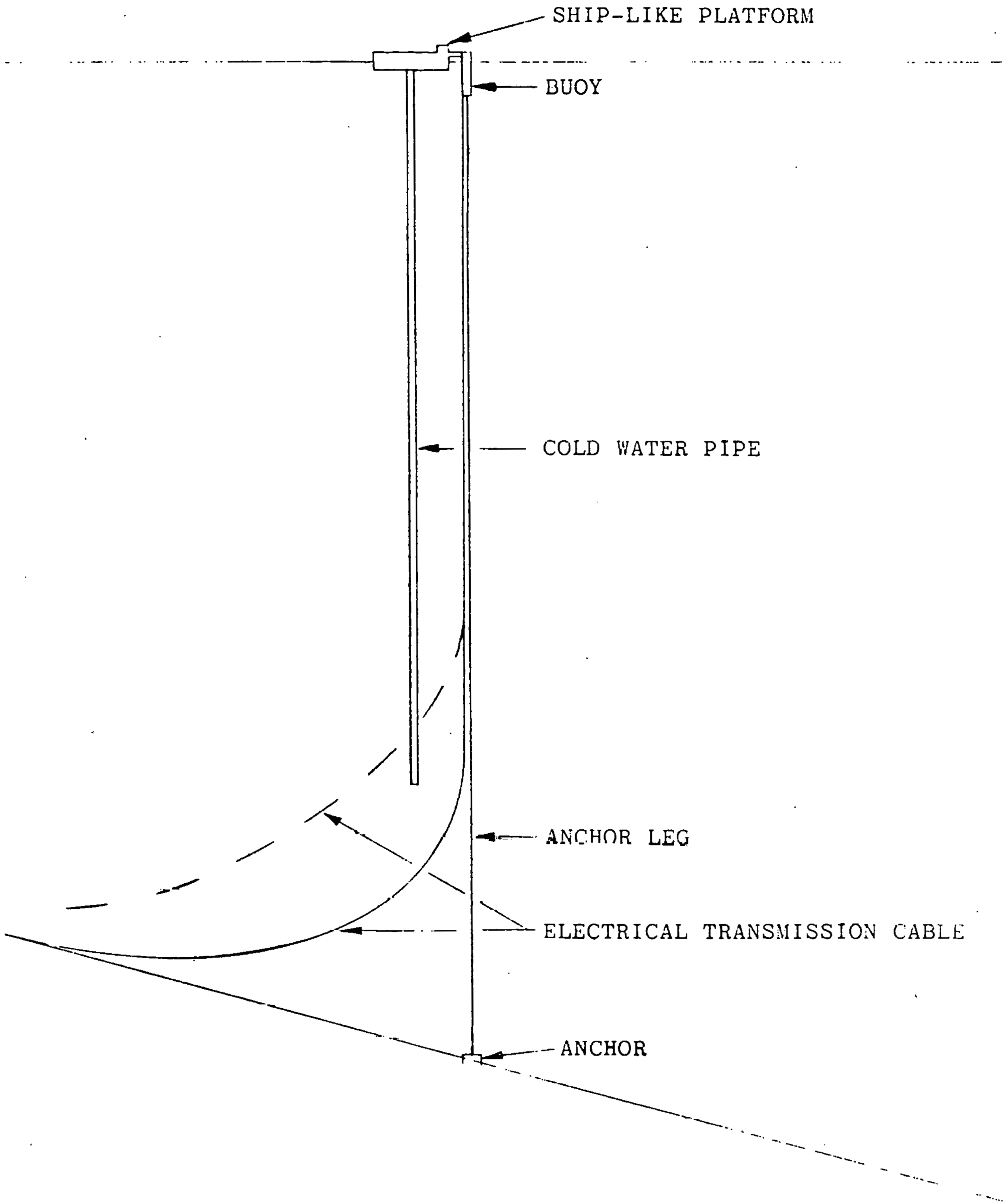


Fig. 4-4 Failure Mode Study for Single-Point Moor

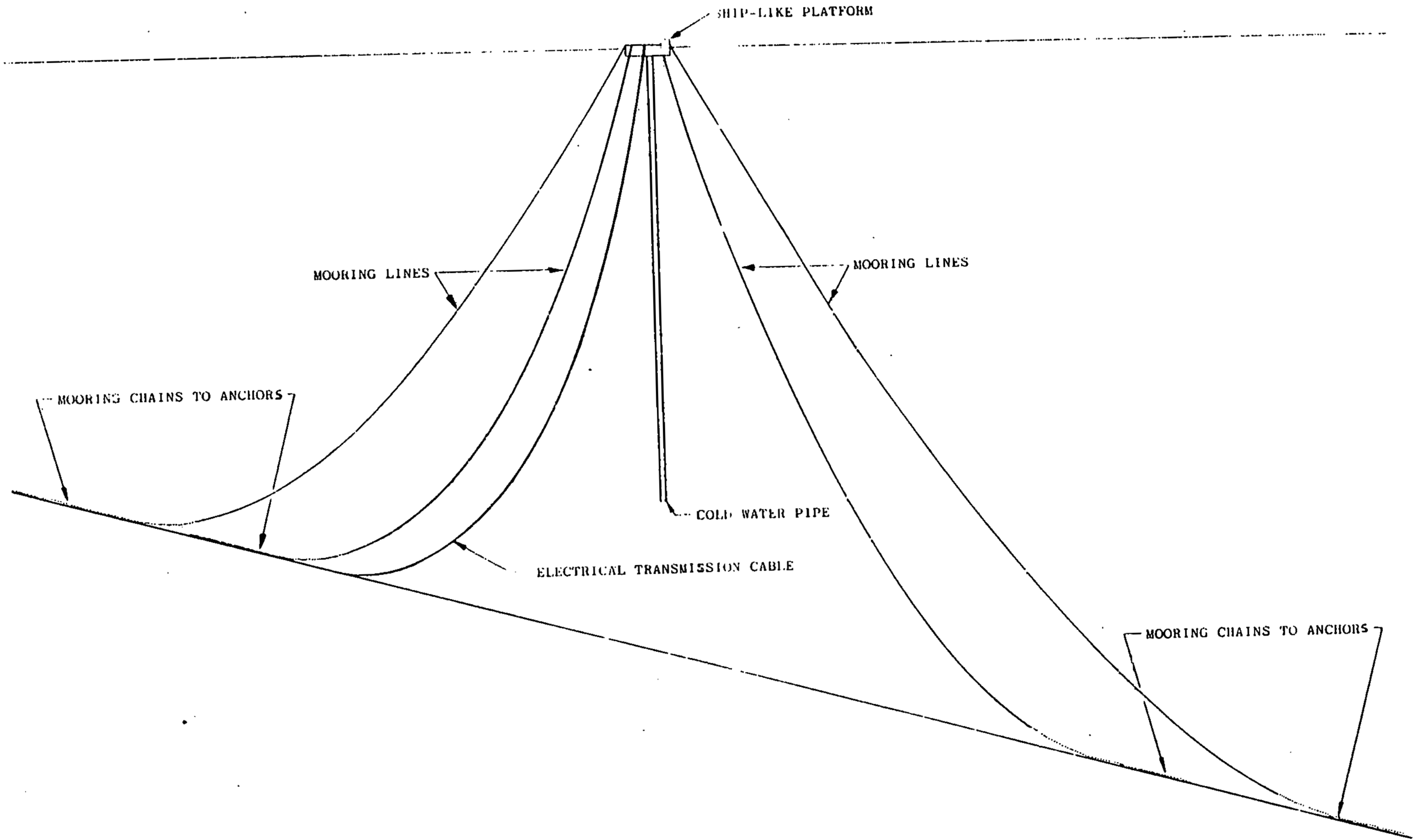


Fig. 4-5 Failure Mode Study for Multiple-Point Moor

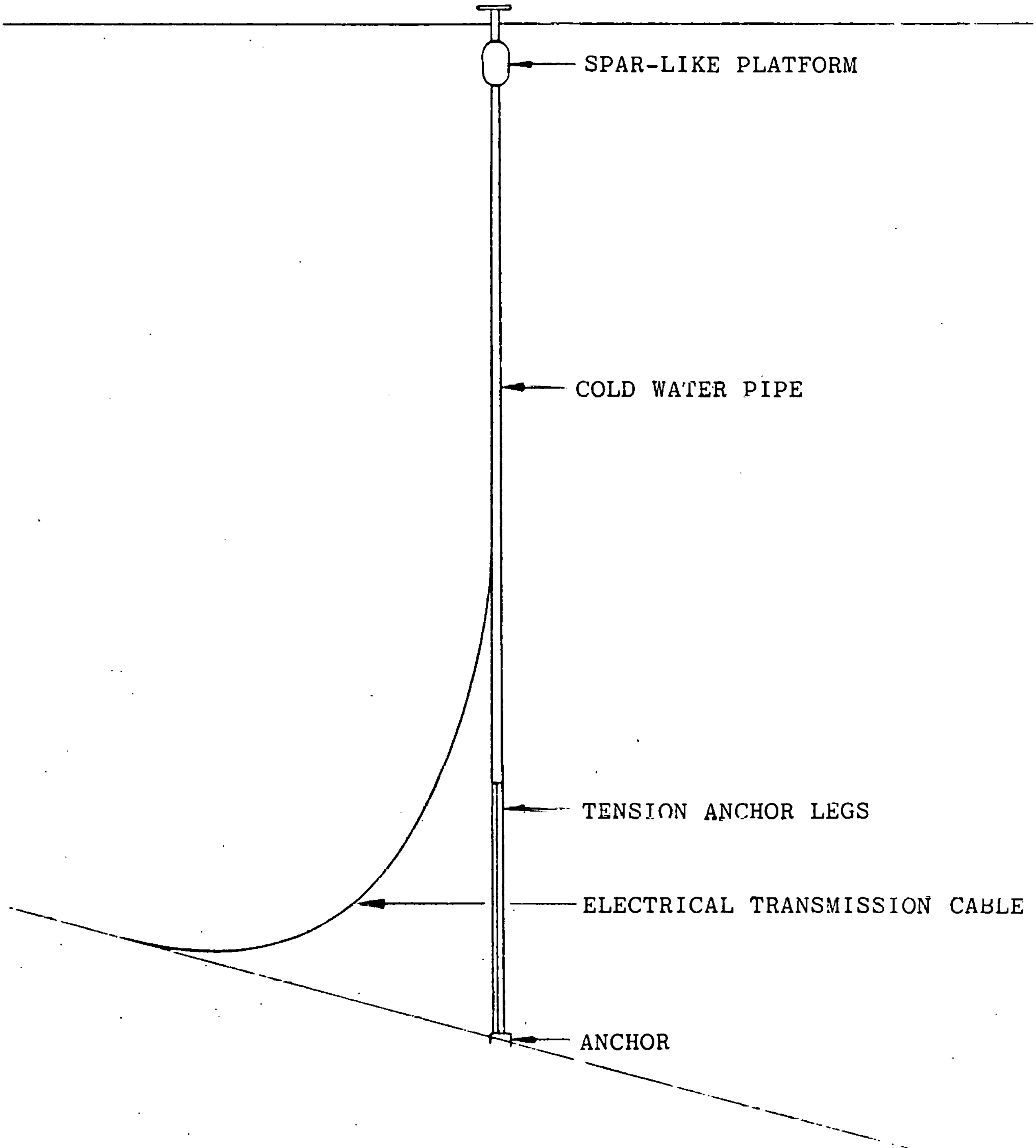


Fig. 4-6 Failure Mode Study for Tension-Anchor-Leg Moor

An assessment was prepared by listing the failure modes on a matrix abscissa. The risk conditions, risk reduction opportunities, and criticality determinants for each of the basic concepts were listed on the ordinate, as shown in Tables 4-5, 4-6, and 4-7. Those risk conditions, risk reduction opportunities, and criticality determinants that could be effective were identified under each failure mode. Identification resulted from a study of the concept drawings and selected scenarios, extending from transportation through operational phases under normal and contingency conditions. High numbers of identified risk conditions or high probability of failure produced an assigned risk factor of 10 for that failure mode. The inherent and available risk reduction opportunities were reviewed to determine the degree to which they could be used to compensate for the risk conditions. The risk reduction factor was deduced, listed under that failure mode, and subtracted from the risk factor to derive the net risk factor. Criticality factors were determined and listed under each failure mode. Finally, the risk-criticality factor was calculated for each failure mode by multiplying the net risk factor by the criticality factor. The risk-criticality factors were 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. Variations to the three basic concepts were similarly assessed by deducing difference values, accounting for those characteristics which were unique. These tables together with background data on deep water moorings are presented in Appendix D.

$$\text{Risk-Criticality Factor} \triangleq (\text{Risk} - \text{Risk Reduction}) \times \text{Failure Criticality}$$

4.2.3 Failure Modes

A failure mode is the event from which functional failure of the moor can result. The failure modes, potentially operative in one or more of the SKSS concepts, are described below. Certain of these failure modes have been operative in one or more ocean projects. The examples presented below validate the chosen failure modes; however, absence of an example is not a sufficient cause for disregarding a plausible failure mode. The OTEC SKSS will

Table 4-5

RISK AND CRITICALITY ASSESSMENT MATRIX FOR SAL-SPM (SHIP)

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	x	x	
Relative Motion	x	x	x	x	x	x	x	x	x	x	
Unproven Compon	x	x	x	x	x		x				
Mult Interface			x			x		x			
Complex Interact		x	x	x	x	x	x	x	x	x	
Complex Environ				x	x	x	x	x	x	x	
Complex Install	x	x	x	x	x	x	x	x	x	x	
RISK FACTOR	10	10	10	10	10	10	10	10	10	10	
RISK REDUCTION OPPORTUNITY											
Environ Measure	x	x	x	x	x	x	x	x	x	x	
Rep Analysis	x	x	x	x	x	x	x	x	x	x	
Load Mitigation	x		x	x	x	x	x	x	x	x	
Self Load "	x	x	x	x	x	x	x	x	x	x	
Redundancy		x		x	x			x		x	
Safety Factor	x	x			x	x	x	x	x	x	
Rep Testing	x		x	x	x	x		x	x		
Detect-Correct		x				x		x	x	x	
Install Simplif	x	x	x	x	x	x	x	x	x	x	
RISK REDUCTION FACTOR	9	9	8	4	8	6	8	4	9	9	
NET RISK FACTOR	1	1	2	6	2	4	2	6	1	1	
CRITICALITY DETERMINANTS											
Personnel Injury					x	x	x	x	x	x	
Downtime	x	x	x	x	x	x	x	x	x	x	
Recovery Cost	x	x	x	x	x	x	x	x	x	x	
CRITICALITY FACTOR	2	2	2	1	10	10	10	10	10	10	
RISK-CRITICALITY FACTOR	2	2	4	6	20	40	20	60	10	10	172

CONCEPT RISK-CRITICALITY FACTOR: 172 SAL-SPM
SHIP 156 MAL-SPM

Table 4-6

RISK AND CRITICALITY ASSESSMENT MATRIX FOR MAL-MPM (SHIP)

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
SHIPS 104 MAL-MPM-Active Tensioning

Table 4-7

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

SPAR

110 TAL Monopod

82 MAL-MPM

120 MAL-MPM-Activo Tensioning

operate under unique conditions which could motivate uncommon failure modes, if appropriate risk reduction opportunities are not exploited.

The labels, shown in parentheses after each failure mode, are used to identify that failure mode in the assessment matrices. A summary of high-capacity, deep ocean mooring experience is presented in Appendix III.

Electrical Transmission Cable Damage by Repetitive Flexure at Seafloor Contact (ETC DAM-FLR). This failure results from work hardening and breakage of the copper conductors as the ETC is repetitively layed and unlayed from the seafloor beneath the platform by platform motion. There have been such failures of transoceanic cables during splicing operations. A related mode is entanglement of the cable on rock outcroppings and on itself due to slack cable accumulation beneath the platform. Small-radii flexure or hockles will result from sudden retensioning by the moving platform. Such modes are the likely cause of cable failures during installation of the Azores Fixed Acoustic Range (AFAR) and the Long Range Acoustic Propagation Project (LRAPP) array, conducted in water depths of approximately 1,500 and 15,000 ft, respectively.

Electrical Transmission Cable Damage by Cold Water Pipe (ETC DAM-PIPE). This failure could result from an improperly positioned ETC and the end motion of the cold water pipe, driven by counter-currents, vortex shedding, and/or partial blockage of the cold water inlet.

Electrical Transmission Cable Damage by Mooring Leg (ETC DAM-LEG). This failure could result from an installation error in which the ETC is layed over one of the mooring legs at a point which rises and falls with ship motion. A related failure could result from improper connection of the ETC to a mooring leg, such that the ETC would be cycled in tension or abraided as the leg is repetitively loaded.

Electrical Slip Ring Faulting (SLIP RING FAIL). This electrical failure would result from the failure of seals and other moisture control devices. There have been unconfirmed, verbal reports of winch-mounted slip ring failures, involving substantially less current and voltage than those required by the OTEC system.

Anchor Pullout or Drag (ANCH PULL OUT). This failure could result from the inability of seafloor soils to generate adequate strengths for resisting high combined static and dynamic loads. The grouted pile anchor of a shallow water submarine tender mooring failed off Rota, Spain, in 1971. The apparent cause was error in placement and grouting. Liquefaction of soil by earthquakes and other vibratory forces, such as those caused by vortex shedding, is a plausible cause of anchor pullout or drag, particularly when the static loading has a large, vertical component.

Anchor Leg Damage by Tension Cycling, Flexure, Wear, Abrasion, and/or Corrosion (LEG DAM-MULT). This failure mode could result from overtensioning and strength degradation due to cyclic fatigue, small-radii bending, hockling, seafloor and intercomponent wear and abrasion, and corrosion. There have been failures during operations of three Navy Squaw moorings after an average of 5 years service, each. These were in water depths ranging from 3,500 to 6,000 ft. The submarine was held 200 to 300 ft below the surface off San Diego, a relatively benign environment. The first failure was traced to a hull padeye. The other two failures were generally attributed to either the mooring lines or fittings. Mooring details are presented in Appendix III.

A failure could result from the relatively low compliance of the TAL monopod moor. Platform motion could set up reinforced compression waves in the pipe leg and result in buckling failure.

Anchor Leg Damage by Cold Water Pipe (LEG DAM-PIPE). This failure could result from the end motion of the cold water pipe, caused by countercurrents, vortex shedding, and/or partial blockage of the cold water inlet.

Mooring Connector Damage by Tension Cycling, Flexure, Wear, and/or Corrosion (MOOR CONN DAM). Failure could result from excessive dynamic tensions imposed by the platform, localized flexure, wear, ship or connector impact, cyclic fatigue, and corrosion.

Buoy Damage by Tension Cycling, Flexure, Wear, and/or Corrosion (BUOY DAM MULT. Failure could result from excessive dynamic tensions imposed by the platform, localized flexure, wear, ship or connector impact, cyclic fatigue, and corrosion.

Ship Connector Damage by Tension and Flexural Cycling, Wear, Abrasion, and/or Corrosion (SHIP CONN DAM). This failure could result from overloading and strength degradation due to cyclic fatigue, wear, and corrosion.

4.2.4 Risk Conditions

A risk condition is an inherent feature that increases the probability of one or more failure modes becoming operative. The risk conditions described below are known contributors to failures of deep ocean moorings and other ocean facilities. All must be carefully considered and compensated if acceptable reliability is to be achieved.

High Pretension. Structures that operate at high stress levels tend to exhibit increased corrosion rates as well as decreased fatigue life under superimposed dynamic loading. This condition was probably operative in the Squaw mooring failures.

High Dynamic Tensions. This condition results in reduced fatigue life. In anisotropic structural elements such as wire rope, this condition increases abrasion, wear, and corrosion rates. Tension variations that carry such structures into a slack condition will produce hockles and extreme sudden strength degradation. This condition was operative in the LRAPP failure.

High Relative Motion. This condition generally tends to increase the probability of damaging component and subsystem interactions, such as impact, wear, abrasion, hockling, connector misaligned loading, and dynamic amplification of loading. Numerous failures of instrumentation moorings have resulted from this condition.

Unproven Components. The high failure history of "first ocean use" components demonstrates that there is greater risk incurred in their use unless stringent compensatory actions are taken to qualify them for use at sea.

Multiple Series Interfaces. Generally, physical interactions at connections are more complex than those within continuous structures. System reliabilities tend to decrease with increasing numbers of components in series.

Complex Interactions. Systems with complex physical interactions are more difficult to analyze, design, test and develop, resulting in decreased confidence level and reliability.

Complex Environment. There are localized regions of the ocean that are not adequately represented by the available, low-frequency, generalized measurements of the gross area or by localized data taken for other than structural design purposes. There are numerous examples of underdesign due to the use of nonspecific environmental data or data that did not represent the design conditions. This was a major contributor to the catastrophic failure of the Texas Towers off the U.S. Atlantic Coast. These towers had been a part of the early warning air defense system. The Texas Tower on Plantagenet Bank, designed for a 45-ft wave, was hit by a 70-ft wave; it survived only because an excessive factor of safety had been applied in the course of design. Because the OTEC sites are chosen for highest temperature differentials, abnormal environmental conditions may occur and should be carefully defined.

Complex Installation. Complex interactions between ocean structural systems and installation systems account for more ocean facility failures than any other single cause. The Seaspider Tri-Moor, intended for 18,000 ft of Hawaiian water, failed during construction. Time consuming leg float attachments lead to human fatigue, with the onset of darkness and adverse weather. The installing ship backed over a surface-layed mooring leg, causing irreparable damage and abortion of the project. The LRAPP array failed electrically due to cable damage during installation. During AFAR I, an antenna array was accidently dropped 1,500 ft to the seafloor. Two deep sea cables were faulted as they were layed off seamount. A three-legged instrumentation moor was damaged beyond use. Appendix III summarizes some deep ocean ship moors that failed as a result of damage during installation.

4.2.5 Risk Reduction Opportunities

A risk reduction opportunity is an action which can be taken to reduce the risk conditions that are potentially operable in one or more of the concepts.

Environmental Measurement. Because the Modular Experimental Plant will not be installed until 1985, there is time to obtain several annual cycles of localized and specialized environmental data. Also, there is the prospect of obtaining data from a "near-miss" hurricane.

Representative Analysis. Validated analytical techniques are available for predicting many of the mooring system responses.

Environmental Loading Mitigation. Certain concepts respond to minimize the imposed environmental loading. Within these and other concepts, detailed features can be introduced to further mitigate loads. Environmental loads are defined here to include any effect of the environment which tends to increase failure risk.

Self-Loading Mitigation. Certain concepts permit the use of geometry to minimize the points, level, and complexity of structural self-loading.

Redundancy Incorporation. Certain concepts include independent members. Failure of one member will result in load transfer to another. In some cases, this will defer the failure consequence until repair can be performed. In others, it reduces the criticality of failure.

Safety Factor Application. Certain concepts permit the use of large safety factors in designing some components. In others, functional interference or the limitation of space, technology, manufacturing capability, and/or economics limit the safety factors that can be applied.

Representative Testing. Validated testing techniques are available for describing the response of some components and assemblies. These must be used for development purposes where analytical techniques do not provide the required level of confidence. Representative testing must be progressively used up to and through the installation operations to properly qualify components, assemblies, and the SKSS.

Detection and Correction. Certain components lend to the detection and correction of incipient failures better than others. Prevention of failure can occur through operational adjustments, repair, or replacement. The inherent ability to detect and correct should be extended through indirect observation and rapid replacement devices and techniques.

Installation Simplification and Control. Certain concepts are inherently simpler to install, requiring fewer operations that must be closely coordinated in time and space and fewer critical procedures that must be performed by personnel beneath the water surface. Certain concepts require only a relatively simple extension of proven techniques. In these and other concepts, the interfaces between the structural and installation systems and the operational procedures must be planned for maximum simplicity. Installation personnel must be thoroughly trained in all normal and contingency procedures. Unavoidable, complex procedures should be authoritatively directed by a field-experienced engineer who has also directed the planning and engineering effort so that unpredicted responses during installation can be promptly compensated.

4.2.6 Criticality Determinants

Failure of the SKSS would produce substantial, adverse impact upon the OTEC Program. The severity of impact depends upon the type and extent of failure, as measured by criticality determinants. The three principal criticality determinants are personnel injury, operational downtime, and cost to recover operational capability.

4.2.7 Results and Conclusions

The lowest risk-criticality factor mooring for the ship is the multiple-anchor-leg multiple-point mooring, rotary or turret. Discrimination between the turret and rotary variations is not possible at the concept level. The multiple-anchor-leg multiple-point moor (MAL-MPM), MAL-MPM active tensioning, multiple-anchor-leg single-point moor and single-anchor-leg single-point moor follow in that order. The catenary single-anchor-line single-point moor does not have sufficient predicted reliability because of the potential for slack line entanglement and hockling.

For the spar platform, the MAL-MPM has the lowest risk-criticality factor, followed by the tension-anchor-leg moor (TAL) or TAL-monopod and the MAL-MPM active tensioning. At the concept level there is no discrimination between the TAL and the TAL-monopod. The catenary single-anchor-leg single-point moor is unacceptable for the reasons cited above.

While there have been many, premature failures of deep ocean ship moors, there have been important successes with such moors and other deep ocean facilities. Although the OTEC SKSS requirements are more stringent than those imposed upon the successful deep ocean moors, a highly disciplined program of risk reduction will produce a successful SKSS with an acceptable level of reliability.

One approach to developing the SKSS is to extend the capabilities of proven mooring systems to satisfy the SKSS depth, duration, and other requirements. Another is to introduce technologically advanced materials after components that use these materials have been subjected to extensive development and qualifications testing. With installation in 1985, it is possible to develop the state-of-art in certain areas. Consideration of additional failure modes would be necessary. In areas of uncertain outcome, "extensional development" of seaproven components should be undertaken. From the concept level of detail, it appears that acceptable reliability could be achieved with dead-weight anchors and combination legs of wire rope and chain. This conclusion will be reviewed after preliminary designs are completed and operating conditions are further defined.

4.3 LIFE CYCLE COST ANALYSIS

This section comprises three subsections. The first discusses the approach to conceptual life cycle cost (LCC) computation developed in the course of Task I, the second describes the method that will be used to estimate the cash flows used by the LCC model, and the last summarizes the approach to be followed in comparing the LCCs of the various SKSS designs.

4.3.1 Life Cycle Cost Computation

The analytical procedure followed in calculating LCCs can be best explained by reference to Fig. 4-7, which illustrates the basic LCC model chosen in Task I. The main driver in the model is the disbursement schedule, representing the estimated cash flow stream associated with a given SKSS design. This cash

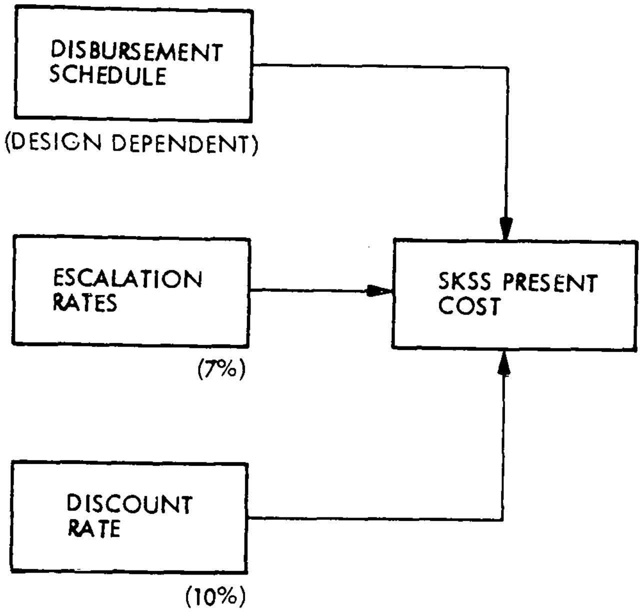


Fig. 4-7 Life Cycle Cost Model

flow stream is estimated in 1979 dollars. Established guidelines for the estimation of the various entries in this schedule are discussed in the next section. All items in the disbursement schedule are then inflated to take into account the cost escalation up to the year in which the individual cost component will be incurred, then discounted back to 1979 to obtain the present value of the (future) cash disbursement. The present value of all costs associated with a given SKSS design is then simply the sum of all such cost items. As all SKSS designs under consideration are expected to offer roughly equal operational lives, it is not necessary to annualize their associated cash streams for comparison purposes, and the present value of these streams can be used by itself as the figure of merit to be minimized.

As it is rarely possible to give reliable estimates of separate escalation rates for the different cost components, it is assumed here that all costs will escalate at the same annual rate. Letting s be the escalation rate, r the discount rate, and C_J the costs occurring in the year J, the present value of these costs in the year p preceding initial cash disbursements, PC_p, is then given by

$$PC_p = (1 + s)^{(p-1979)} \sum_{J=1}^{n} C_J \left(\frac{1+s}{1+r}\right)^J \quad (4\text{-}1)$$

where n is the financial life of the SKSS, i.e., the number of years in which associated disbursements occur.

In the course of Task I, it was decided to use an escalation rate of 7 percent, applied equally to all cost components. A value of 10 percent has been chosen for the discount rate, reflecting the current cost of money for private utilities. Both figures were taken from information supplied to contractors by DOE in the course of the current OTEC Power System Development II study. For the sake of convenience, the year p was chosen as 1979 for all systems. Equation (4-1) then reduces to

$$PC_{1979} = \sum_{J=1}^{n} C_J \left(\frac{1.07}{1.10}\right)^J \quad (4\text{-}2)$$

It should be noted that n is the same for all SKSS concepts, although some concepts may take longer than others to fabricate and deploy. As the same operational on-line date is assumed in all cases, the cash flows associated with some designs may have zero entries in their first or second year.

In practice, application of the simple model described above is somewhat cumbersome particularly as some of the expenditures occurring during operational years - those associated with insurance and local taxes - are dependent on the amount of initial capital expenditure. To facilitate computation of present values, a computer program developed in the course of the Power System

Development II study will be modified and used for this purpose; primarily, this modification will involve data input and output statements.

4.3.2 Cost Estimation

Estimation of the cash disbursement schedule, from which the C_J's in Eq. (4-2) are calculated, will follow as closely as practicable the preliminary Work Breakdown Structure (WBS) developed in the course of Task I and shown in Table 4-8. The first major element of the WBS includes systems engineering and design activities for the SKSS as a whole, as well as for individual components such as turrets, swivels and buoys, requiring preparation of special designs. The second element, covering all capital cost items required by an SKSS design, will take very different forms for the various designs; no single SKSS concept uses all the items listed under this heading. SKSS deployment costs will include transportation of the SKSS component to the site, as well as its installation and test as a completed assembly, using personnel and support equipment as required. The fourth main WBS element, System Operation and Support, includes both one-of-a-kind and recurring cost elements. Routine inspection, maintenance, and repair activities will take place on a continuous basis over the life of the plant, including expenses for personnel, support equipment and consumables. The third item under this heading, Refit and Modification, is at present undefined, and is included in the WBS solely to take into account the possibility that some such activity may be called for as a result of further OTEC system requirements definition. Finally, the cost of scrapping and final disposition of the SKSS will appear under the last entry of the WBS.

The primary consideration of conceptional cost estimation is to ensure comparability among the various SKSS designs; consequently, the estimation approach to be followed emphasizes the establishment of a common cost base. The approach to be followed in estimating costs will differ for each of the

Table 4-8

SKSS WORK BREAKDOWN STRUCTURE

I. Engineering and Design

1. Component Design
2. SKSS Design
3. Systems Engineering

II. Acquisition

1. Drag Embedment Anchors
2. Clump Anchors
3. Chain
4. Wire Rope
5. Fittings
6. Auxiliary Machinery and Equipment
7. Hawsers
8. Spares
9. Deadweight Anchor
10. Pile Group Anchor
11. Turret
12. Carriage
13. ETC Swivel
14. Buoy
15. Mooring Yoke

III. Deployment

1. Mobilization
2. Installation Operations
3. Diving
4. Demobilization

IV. System Operation and Support

1. Inspection
2. Maintenance
3. Refit and Modification

V. System Disposal

1. Mobilization
2. Removal Operations
3. Diving
4. Demobilization

elements of the WBS. Estimation of engineering and design costs will draw heavily on IMODCO's experience in this area. Manufacturer quotes for capital expenditure items will be obtained whenever practicable. When this is not possible because of the unique nature of some items, estimates will be based on weight and dimensions, using $/lb or $/ft multipliers appropriate to the equipment in question and common to all SKSS designs using such equipment. The activities included in the last three elements of the WBS are typical of offshore and marine operations. Costing of these activies will be done on the basis of operational plans which will dictate personnel and equipment requirements. Again, labor rates and equipment lease charges will be common to all SKSS designs.

It is perhaps well to note that the estimates to be prepared in Task II will not include allowances for contingencies. Such allowances are essentially an implicit measure of cost risk and, as discussed in the next section, cost risk will be considered explicitly when the alternative SKSS designs are compared.

4.3.3 Comparison of Life Cycle Costs

While cost estimates usually attempt to reflect the most likely cost of a product or activity there usually is considerable uncertainty surrounding actual costs. This is particularly true for conceptual designs involving advanced ocean systems, as the designs themselves tend to evolve over time and a large part of the cost is usually associated with deployment and operation, and is consequently affected by weather conditions. This poses some problems in using cost estimates to discriminate among competing concepts, since a design with a comparatively low "most likely" cost estimate could also involve a relatively high risk of substantially higher actual cost. If this risk is not quantified, cost minimization on the basis of "most likely" estimates is a procedure of dubious validity in choosing among candidate designs.

To take into account the above mentioned uncertainty in conceptual cost estimates, more than one estimate will be prepared for each SKSS design concept, and all estimates will be used jointly in evaluating the concepts. Each estimate will correspond to a different set of assumptions concerning the difficulty of implementing the relevant conceptual design and/or of deploying and servicing it after fabrication. At present, it is planned to prepare three separate scenarios for each design concept, corresponding to "optimistic," "most likely," and "pessimistic" assessments of design, fabrication, deployment and operational features of each concept. Should it prove desirable to do so, additional scenarios will be formulated for specific designs. Probability values will be associated with each scenario and, consequently, with each cost estimate for a given design. An expected value cost estimate (in effect, the sum of the various cost estimates weighted by their respective probabilities of occurrence) will then be calculated, and this will be used as the primary cost measure for comparisons among the various designs.

Figure 4-8 summarizes the process to be followed. A baseline design will be combined with various scenarios, as discussed above, to generate a vector of

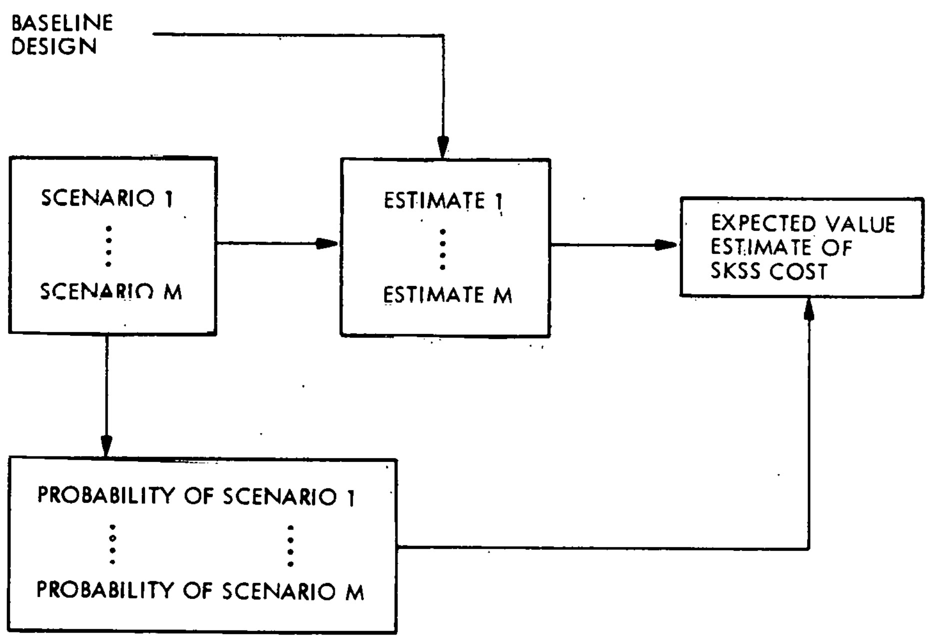


Fig. 4-8 Expected Value Cost Estimate Calculation

cost estimates; at the same time, the probability of occurrence of each estimate will be assessed to generate a vector of probabilities. Finally, the expected value cost estimate will be obtained as the dot product of the two vectors, and this will be used as the overall figure of merit associated with the specific SKSS design.

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Section 5
DESIGN SELECTION

The goal of design selection is to identify the mooring system concept which satisfies requirements with the best combination of risk and cost. The evaluation criteria and selection technique to be applied to the candidate mooring concepts in Task II are presented in this section.

The approach to concept selection for preliminary design consists of three phases: concept assessment, ranking, and final selection. The first and second phases will be conducted in Task II by the LMSC SKSS design team, while the third phase will be completed by NOAA/DOE.

Concept assessment, initiated in Task I and continued in Task II, consists of the design and analysis activities necessary for concept definition and evaluation, including all necessary trade studies, performance and risk/reliability analysis, and life cycle costing. In this phase, any SKSS design that appears highly unlikely to fulfill the top level performance requirements will be eliminated from further consideration in the selection procedure.

Surviving concepts will be ranked in the second phase of the selection process; this phase in turn comprises two separate rankings. The first ranking addresses primarily the costs and risks associated with each of the mooring system concepts themselves, without regard to the costs and risks of the related development programs; the latter are taken into account in the second ranking. Within the first ranking, the costs associated directly with the SKSS are relatively easy to quantify and their expected value will be calculated as discussed in Section 4.3. Likewise, a measure of the relative risk of the various systems is available from the reliability study discussed in Section 4.2. Combining these costs and risks into the overall figure of merit required in the first ranking is a somewhat difficult problem; the approach to be followed in resolving it is discussed below.

The main difficulty in developing a ranking combining cost and risk elements resides in evaluating the implied cost of a given relative risk factor. Theoretically, this can be done by assessing both the probability of occurrence of each specific failure mode and the likely associated downtime and repair costs. This study will attempt to use a variant of this approach, which begins by estimating the probability of failure associated with a given relative risk factor and using this estimate to derive the probabilities of failure implied by other risk factor values. The average downtime and repair costs associated with the various failure modes will then be estimated, and used in combination with the probabilities of occurrence to arrive at an expected value of the implied risk-related costs associated with each design. This cost is then added to the direct cost of each design to result in the figure of merit to be minimized, thus providing the basis required for ranking purposes.

The pitfalls in the method described above are readily apparent, and arise mainly from its use of subjective probability assessments. Given the lack of current experience with mooring systems similar to those required for OTEC plants, in practice there is little choice but to use such subjective assessments in evaluating competing systems; use of subjective probabilities under these circumstances is well established in decision analysis practice.*

An alternative approach applied to the selection of CWP concepts will be used should subjective probability assessment prove impractical. In this approach, both direct cost and risk factors are first normalized by dividing them in each case by the smallest values found for the SKSS designs under consideration, and a weighted sum of the resulting two pure numbers is then used as the (inverse) figure of merit. Of course, the operational meaning of any given value of this figure of merit is difficult to define precisely. More importantly, the resulting rankings are heavily dependent on the weights

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*R. A. Howard, "The Foundations of Decision Analysis", in IEEE Transactions on Systems Science and Cybernetics, Volume SSC-4, Number 3, Sep 1968 chosen. For ranking purposes, a "reasonable" (in the light of engineering experience) value will be used for these weights. Allowing these weights to vary provides a measure of the sensitivity of the result to variations in cost/risk preference. This information can be used in conjunction with the values chosen for ranking purposes to evaluate the stability of the resulting ranking and thus help in framing recommendations for choosing among the competing designs. Of course, it is to be expected that some SKSS concepts will be dominated by others offering both lower cost and risk, thus easing the ranking task.

Once the first ranking is completed, taking into account factors affecting exclusively the SKSSs themselves, a second ranking will be developed to reflect the likely cost and risk to DOE of the development programs associated with each SKSS design. To this effect, OTEC technology factors will be applied to each concept and component to assess the technology development requirements. These factors, used in CWP concept design studies, are as follows:

1. Technology is nonexistent
2. Massive high-risk R&D
3. Extensive relatively high-risk R&D
4. Extensive moderate-risk R&D
5. Nominal moderate-risk R&D
6. Limited offshore experience
7. Nominal low-risk R&D
8. Relatively little R&D requiring no testing
9. Little R&D and no testing
10. Existing technology fully adequate

The resulting two rankings and analytical data will be submitted to NOAA/DOE for use in the final selection of the two systems to go into preliminary design. As the two rankings will reflect very different considerations and involve different decision makers, it is not considered desirable to attempt to derive a single overall quantitative ranking scheme.

Figure 5-1 summarizes the logic flow of the design selection process outlined above. Each SKSS design is first evaluated to determine whether it meets primary requirements, and rejected if it doesn't. Surviving concepts are then ranked separately on the basis of the costs and risks associated both with the designs themselves and with the development programs envisaged to bring them to fruition. These rankings are then submitted to NOAA/DOE for the final design selection decision.

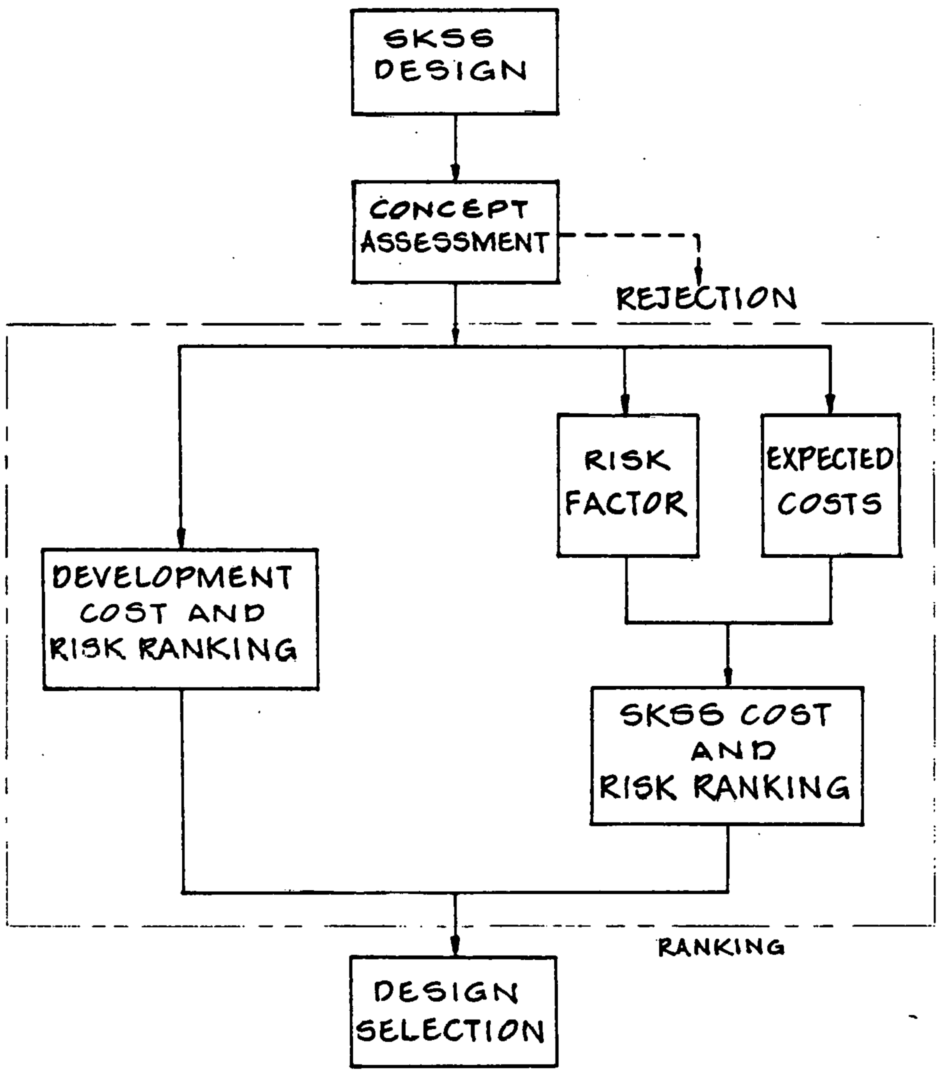

Fig. 5-1 Design Selection Logic Flow

Section 6
CONCLUSIONS AND RECOMMENDATIONS

OTEC SKSS design requirements are defined and presented, including approaches to assessment of performance, reliability, life cycle costing, and concept ranking to be followed in Task II, Concept Design. Analysis of environmental conditions provides formulas for specifying states of wind, wave, and current for a given return period requirement. Design sea states and weather windows are identified.

Design criteria, including material standards, safety factors, and load factors are specified based on accepted practice in offshore, single-point-mooring terminal design. Static analysis indicates that holding power is achievable with a combination wire rope and chain anchor leg. Platform drag estimates indicate total horizontal force is not in excess of 0.8×10^6 lb, with the ship drag greater than that on the spar.

Trade studies as well as static and dynamic analyses to be conducted in Task II are defined. Results of a reliability assessment indicate that the multiple-anchor-leg/multiple-point turret ship moor has the lowest risk-criticality, while that for the spar is the multiple-anchor-leg/single-point moor. The catenary single-anchor-leg/single-point moor has insufficient reliability and watch circle capacity and will therefore not be considered further. Failure modes analysis, risk, risk reduction opportunities, and criticality failure are defined and treated. Life cycle cost methodology is presented, indicating the use of three costing scenarios to identify expected values of SKSS costs.

The inadequacy of data in certain areas was revealed in the conduct of this Task. In the area of environmental conditions, additional data are required on bottom soil properties, particularly depth of sediment, bearing, and shear strengths. Data are required on current profile, including speed and direction variation with depth and month of the year. The seafloor 2 miles southeast of the Punta Tuna site is flat, albeit almost 2,000 ft deeper. This area, known as the Virgin Islands Basin, is recommended as an alternate site, particularly if the sloped bottom off Punta Tuna poses an excessive design constraint. Finally, the slowly varying wave drift force exerted on the platform is a significant portion of total environmental load, yet force and moment coefficients are inadequately treated in the literature. A model test program to ascertain the magnitude of such loading on the ship and spar platforms is recommended.

Appendix A

PRELIMINARY REQUIREMENTS ON THE OTEC STATIONKEEPING SUBSYSTEM IMPOSED BY THE ELECTRICAL TRANSMISSION SUBSYSTEM

Simplex Wire and Cable Company
Newington, N.H.

Development Engineering Report No. 65
28 March 1979

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A.1 INTRODUCTION

The Electrical Transmission Subsystem (ETS) for the 40-MW OTEC plant includes a transmission cable which extends from the plant to the ocean floor. This portion, known as the riser cable, is of primary concern in interfacing the ETS with the stationkeeping subsystem (SKSS). The purpose of this report is to discuss possible general configurations for the riser cable and to define requirements for interfacing it with the SKSS. Two potential cable types are being considered for the 40-MW OTEC plant: a three-conductor cable or four single-conductor cables. If a decision is made to provide the 40-MW OTEC plant with an ETS closest to state-of-the-art, a three-conductor cable will probably be chosen. If the decision is to provide an ETS more nearly like a potential 400-MW system, the four-cable system will probably be chosen. Both types must be considered strong candidates at this stage of conceptual design.

Both types would provide for three-phase alternating current transmission. The four cables would provide a spare cable; for the three-conductor cable, a second cable would be necessary to provide a spare. The reliability, repairability, and handling characteristics of the system can be potentially improved by using single-conductor cables. Further, the single-conductor cables may provide more realistic information about potential performance of a 400-MW cable system, which would in all probability be a single-conductor cable.

Many of the interfacing considerations are affected by the presence of four separate cables. It is important to remember that multiple riser cables may be present when considering the ETS/SKSS interface. Preliminary cable design work indicates that a three-conductor cable for the 40-MW OTEC plant might be about 6 inches in diameter and 4.5 pounds per linear foot weight in water. A single-conductor cable for the 40-MW plant might be somewhat oversize to more closely simulate a 100- to 400-MW cable, and might be about 4 inches in diameter, and 4.5 pounds per foot in water.

Fatigue behavior of cable as a whole and the insulation material in particular is not known for power cables suitable for transmission of 10 to 40 MW. Some limited flex testing of cable in this power class is reported in Reference A-1. Under contract to DOE, Simplex is just beginning a program to test the resistance of suitable power cables to tension, bending, and twisting fatigue. Until the results of this test program are available, the fatigue resistance of the cable is subject to some speculation. However, the aim of the testing and development program will be to develop a cable which can resist both mechanical fatigue failure and electrical breakdown under mechanical fatigue conditions.

A.2 OPERATIONAL LIMITATIONS ON PLANT WATCH CIRCLE DUE TO ETS AND PERMISSIBLE EXCEEDANCES

The watch circle requirements as specified by LMSC Proposal D085241 for the Pt. Tuna, P. R. site are:

Water depth: 4,000 ft
Watch circle radius: 400 ft
Return period of design storm: 3 years

These requirements seem consistent with any reasonably anticipated power cable system. However, several contributing factors should be noted, and some additional requirements are necessary.

The first aim of watch circle limitation is to limit tensions in the riser cables to levels at which both static and dynamic loads can be tolerated by the strength components and insulation of the cable. Exceedance of nominal watch circle during unusual storm conditions may contribute both higher than nominal base tension in the riser cable and higher than normal dynamic forces due to wave action associated with the storm. This combination presents potential risk of fatigue failure. Therefore, it seems necessary at this time to limit the duration of watch circle exceedances to a few hours (say 3 hours). Design of cable system dimensions can probably accommodate watch circle of up to 800 ft for these durations. However, some cable system configurations will be more suitable for these large exceedances than will others.

It is possible, but unconfirmed, that the riser cable might successfully survive high mechanical stress conditions if it were not energized electrically at the time of the high stresses. This possibility will be investigated in the forthcoming test program. Although this factor is still speculative, it may help give some safety factor to cable fatigue resistance under unusual conditions of watch circle exceedance.

In addition to the limitations due to tension and fatigue loading, the watch circle must be consistent with the riser cable system layout in that physical contact or chafing of the cable on either portions of the plant (at other than design attachment points) or the mooring system must be avoided. This is necessary to prevent physical damage to the cable, thus avoiding decreased strength and increased risk of corrosion of the metallic elements of the cable nearest its outer surface. It also avoids damage due to uncontrolled bending or impact. In order to avoid these contacts it is obviously necessary to allow for potential movements of the cables, plant, and moorings due to currents, storm winds, and storm waves. In particular, a cable deployed in a catenary must have sufficient space to allow for swing of the cable. While this requirement does not put a hard and fast limit on watch circle, it must be considered in evaluating the performance of any SKSS/ETS combination. Another related requirement is that the movement of the plant in its watch circle shall not produce too much twisting of the cable. A cable deployed in a catenary from plant to ocean floor will be twisted by the movement of the plant relative to the touchdown point of the cable. While this twist is in general relatively small, it must be considered in the total potential twist on the cable. This will be further discussed in "cable twist and torque considerations".

A.3 DEPLOYMENT, REMOVAL, AND INSPECTION CONSIDERATIONS

It has been assumed that the riser cables will be deployed after the SKSS is in place. This is not an absolute necessity, but the complications necessary to insure control and protection of the cables during a simultaneous deployment of a mooring and the riser cables, and to coordinate the vessels and simultaneous lowering operations, would make such an operation unattractive. As previously mentioned, there is a strong possibility that four separate cables will be deployed. With these considerations in mind, the following requirements for the deployment and/or repair of the ETS as it affects the SKSS can be foreseen. Ample physical clearances must be available for the cables during deployment. Each cable must be lowered from a surface vessel and cannot cross over mooring lines while descending. Similarly, any other lines or anchors necessary for the cable support system must have clearances available. Clearances for submarine work vehicles must be allowed if connections of any ETS components, or attachments to any other subsystem components must be made during or following cable deployment. Assuming that space is available for the ETS to operate once installed, these requirements for installation should not be a particular problem to subsystem coordination.

Repair, removal, or inspection operations on the ETS should impose only one additional requirement on the SKSS beyond those associated with deployment. Any physical contact with a cable for repair type operations will require that the cable be de-energized and sufficiently separated from the remaining live cables so that workers and equipment can operate safely. In the case of a three-conductor cable this would mean that no power could be transmitted during repair operations. In the case of four separate cables, this would mean that any cable being retrieved should have clearances to avoid contacting any of the live cables.

A.4 POTENTIAL ELECTRICAL TRANSMISSION SUBSYSTEM CONFIGURATIONS

Three basic methods of configuring the riser cable and its support subsystem have been considered. A brief description of these configurations is presented to allow early integration of basic ideas of SKSS and ETS.

The simplest system would be a cable descending from the OTEC plant in a substantial catenary as shown in Fig. A-1.

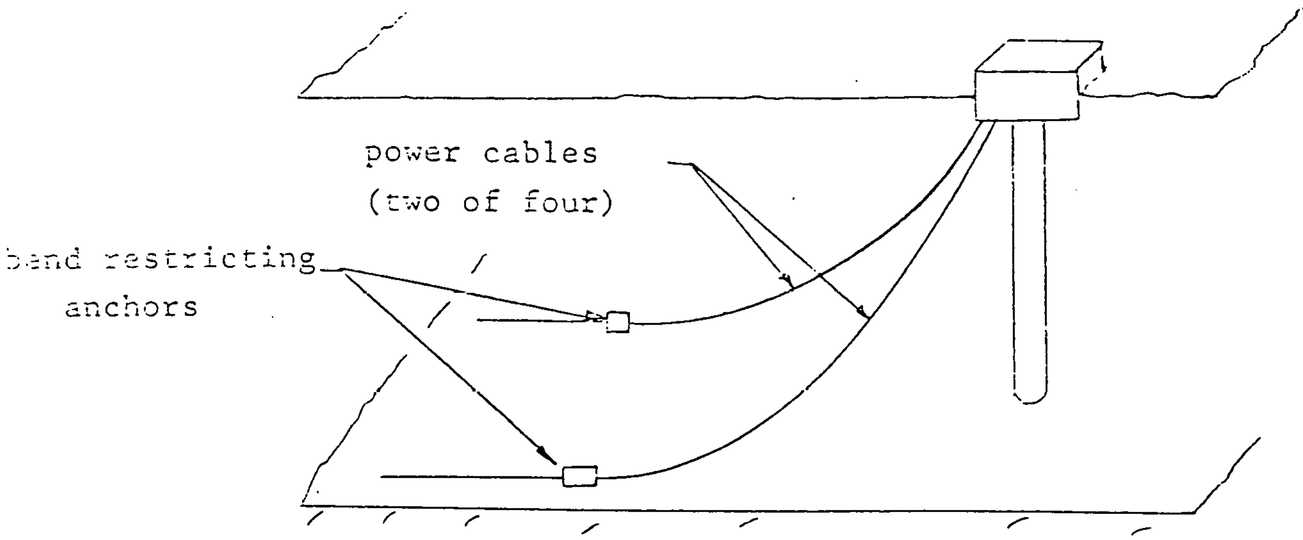

Fig. A-1 Catenary Configuration

This system has a limited ability to accommodate extended plant watch circles, but might be suitable for a 10 percent watch circle with little room for exceedances. It would require sufficient spaces within the SKSS to deploy four separate cables. An anchor on each cable might be necessary. The horizontal distance to such an anchor (or the nominal touchdown point of the cable if an anchor is not used) from the OTEC plant would be in the range of 1 to 1.5 times the water depth.

Another system considered a good possibility is the standoff buoy support shown in Fig. A-2.

An anchor and anchor line will probably be necessary. Within the basic configuration, a great variety of combinations of cable length, buoy-to-plant distance, and vuoy depth are possible.

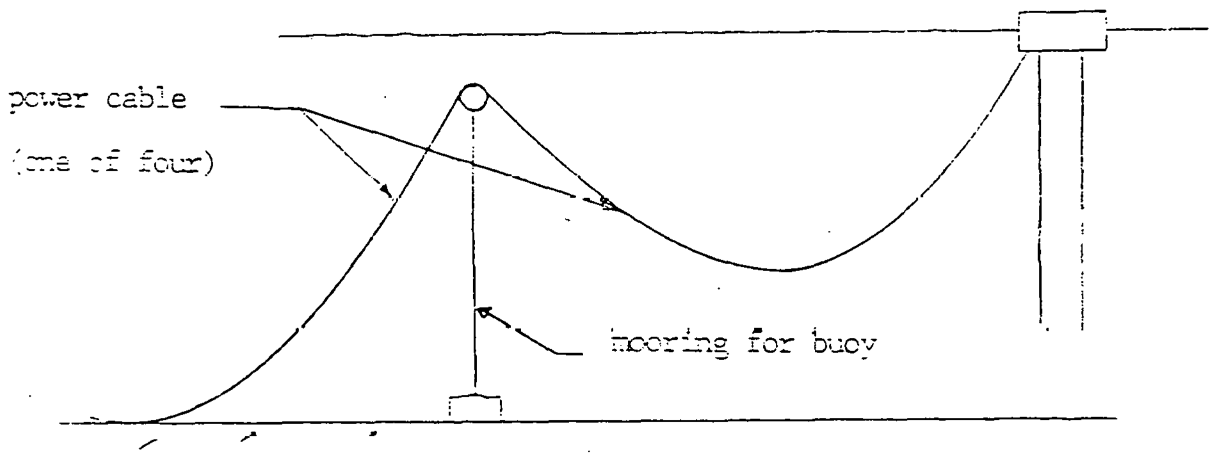

Fig. A-2 Standoff Buoy Configuration

As currently envisioned, the horizontal distance from plant to buoy would range from a minimum of 2,000 ft to a maximum of 4,500 ft. The horizontal distance from buoy to cable touchdown point will probably be from 3,000 to 6,000 ft. The combination of separation distance and cable length can be tailored somewhat to limit tensions induced in the cable, to avoid interferences with the SKSS, or to detune mechanical resonances of the power cable. Within the limits mentioned, a greater buoy-to-plant distance is combined with a proportionally longer length of cable to accommodate a larger watch circle. The depth of the buoy should be at least 200 ft below the surface to avoid surface wave action, and might be designed for a depth of as much as 2,000 ft, if necessary. A deep buoy configuration might improve dynamic characteristics of the riser cable system, and might reduce the length of riser cable actually suspended.

A third basic method of configuring the riser cables is a vertical descent to the ocean bottom. This would probably not be used unless mooring lines followed a similar pattern. An anchor for the cables at the ocean bottom would almost certainly be required. Methods of deploying this anchor, or attaching the cables to an anchor already in place, must be consistent with the installation plans for plant and mooring. Elastic behavior of the electrical cables and the mooring lines must be carefully matched to avoid overtensioning the cable. Also, any condition which causes slack cable at the anchor must be avoided. Standoff devices may be necessary to prevent contact or chafing of the riser cables on the CWP or mooring lines.

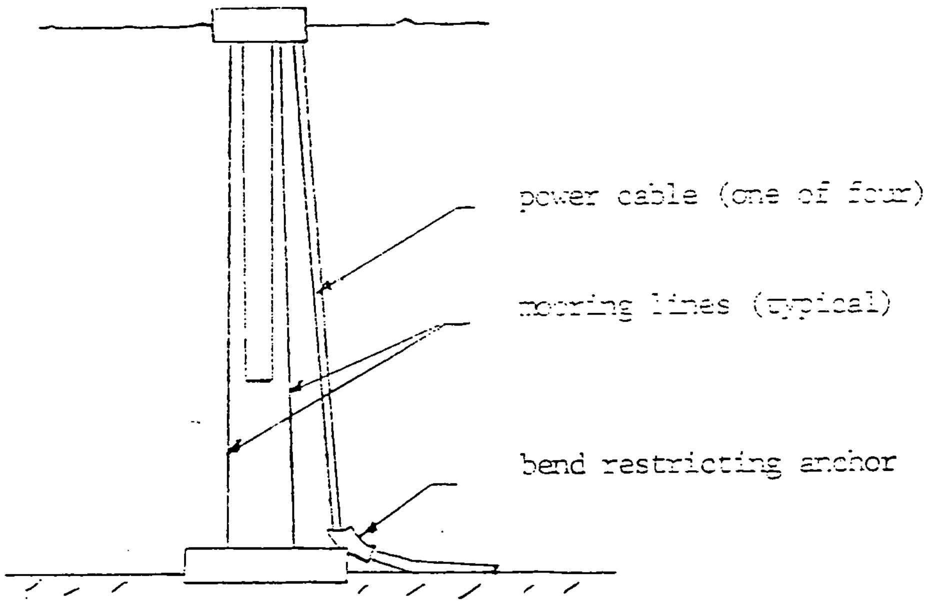

Fig. A-3 Vertical Descent Configuration

The proposed mooring systems which allow the plant to rotate about a single point moor or turret deserve one special note. Such a mooring arrangement would necessitate a swivel connection capable of transmitting 40 MW of electrical power. Operating experience with any such device at the necessary voltage and power level is not available. The possibility of extending such a device to the 400-MW level is extremely limited.

A.5 RISER CABLE TWIST AND TORQUE CONSIDERATIONS

The question of the ability of a high-voltage power cable to accommodate twist is one of the biggest unknown factors to be addressed in the forthcoming test program. Twisting of the cable is expected to affect the interface of the power conductor and its insulation. Electrical stresses are at their highest level at this interface. The presence of microscopic voids in the insulation at this interface could have drastic effects on the electrical life of the insulation. Also twist will have a contribution to fatigue of the strength elements of the cable. The important parameter in considering twist of cables is usually degrees of twist per unit length of cable. However, because of the probability that the OTEC riser cable will be configured in a catenary which will not see uniform twist over its length, total twist of the end of the cable is probably more significant. The greatest consideration in limiting rotation of the end of a cable may be the physical interference of four riser cables with the plant and each other. If the cables are attached to a portion of the plant that is allowed to rotate, a working limit of plant rotation of 90 deg is certainly necessary to avoid physical interferences between cables or between cables and plant structure. This working limit represents long term heading changes of the plant. Working limits on twisting motions at wave-excited frequencies are harder to quantify because the fatigue of the cables is poorly understood. However, the aim of the development program will probably be to develop a cable capable of withstanding ·10 det of dynamic rotation for a number of cycles appropriate to the OTEC plant and SKSS designs. A clearer definition of what the motion characteristics of the 40-MW plant and its SKSS might be will be of great assistance to final design of the 40-MW cable and the test program for it.

A.6 REFERENCE

A-1 C. A. Pieroni and B. W. Fellows, "Life Evaluation of a 35 kV Submarine Power Cable in a Continuous Flexing Environment," Ocean 77 Conference Record, Paper 24C, Oct 1977

Appendix B

OTEC STATIONKEEPING SUBSYSTEM (SKSS) PERFORMANCE SPECIFICATION

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1. SCOPE

This specification establishes the performance and design requirements for the Stationkeeping Subsystem (SKSS) for the 40-MW(e) Modular Experiments Plant. In the development of OTEC SKSS concept and preliminary designs this specification will be developed as a definitive specification for SKSS.

2. APPLICABLE DOCUMENTS

2.1 Preliminary Design for OTEC Stationkeeping Subsystems, Technical Proposal, LMSC-D085241, 9 August 1978.

2.2 Preliminary Engineering Design of an OTEC Pilot Plantship Vol. D - Engineering Drawings, APL/JHU SR-78-3D, November 1978.

2.3 10 and 40 MW Spar Conceptual Designs, Gibbs and Cox, Inc., February 6, 1979.

3. REQUIREMENTS

3.1 SYSTEM DEFINITION

As part of the Ocean Thermal Energy Conversion (OTEC) Program of the Department of Energy, Solar Division, ocean demonstration tests are planned for an OTEC Modular Experiments Plant. This plant will contain OTEC power cycle systems in the 10 to 40 megawatt (net electric) output range. The OTEC plant electrical capacity will be utilized either onboard the platform to develop various end products, or in the stationary, electric cable mode, the output will be cabled ashore to an electric grid.

3.1.1 General Description

The Stationkeeping Subsystem (SKSS) is a mooring system for the OTEC Modular Experiments Plant. Moors of this type for coastal, deep water application, generally consist of one or more anchor legs.

The first type, the single anchor leg, single-point moor, consists of an anchor, line, surface buoy and hawser or yoke. The platform is free to swing about the moor. The second type is the multiple-anchor leg, which consists of two or more legs attached either directly to the platform or to buoys. Variations of the multiple-anchor-leg moor include active tensioning, turret, rotary, and single-point moors. The third type of moor is the tension anchor leg, wherein the legs are attached either directly to the platform or to the cold water pipe. A variation of this type is the monopod, wherein the cold water pipe is mounted to an anchor or base plate.

3.1.2 Mission

The SKSS is the mooring system which will hold the OTEC Modular Experiments Plant on-station at the Puerto Rican operational site. In addition to serving the primary function of mooring the plant, the SKSS will be required to support a portion of the Electrical Transmission System, particularly the riser cable itself, depending on the combination of mooring and transmission system selected.

The success of the SKSS will be measured by its contribution to demonstrating that the OTEC plant is capable of surviving one or more hurricanes in its first few years of operation. Such demonstration will contribute significantly to future application of OTEC in tropical waters. In this regard the SKSS will serve as a prototype for mooring the larger, longer design life Commercial OTEC plants.

3.1.3 System Diagrams

N.A.

3.1.4 Interface Definition

The Stationkeeping Subsystem is an element of the Platform System in the OTEC Work Breakdown Structure, as follows:

3.1 Platform System

3.1.2 Stationkeeping Subsystem

The primary physical and functional interface exists between the SKSS and the hull. The moor is attached to the hull, or alternatively to the cold water pipe. A secondary interface exists between the SKSS and the Electrical Transmission System, particulary the riser cable.

3.1.5 Government Furnished Property

N.A.

3.1.6 Operational and Organizational Concepts

Deployment of the Modular Experiments Plant is planned for 1985 in Puerto Rico. The SKSS will be designed by a systems integration contractors in 1980 or '81. This subsystem will therefore be fully integrated in the OTEC plant system design. Concept and preliminary designs for SKSS to be furnished under this contract in 1979 will be an input to the engineering data base for preparation of the RFP for Modular Experiments Plant System Integration.

3.2 CHARACTERISTICS

The mooring system requirements are stated in the following paragraphs in terms of performance characteristics required for the system, physical features and constraints, reliability and other characteristics. These system characteristics are significantly influenced by the mission defined for the Modular Experiments Plant. The plant is a stationary OTEC power plant 40 MW(e) to be moored off Punta Tuna, Puerto Rico for the purpose of transmitting electrical power via a submarine cable to the Puerto Rican grid.

3.2.1 Performance Characteristics

3.2.1.1 Function. The SKSS will constrain the OTEC Modular Experiments Plant 40 MW(e) off the coast of Puerto Rico at Punta Tuna. The limits on constraint will be derived from requirements of the Electrical Transmission System, cold water pipe grounding, cold water pipe - SKSS fouling.

3.2.1.2 Platforms. Two platforms will be moored - the APL plantship as modified and the Gibbs and Cox spar. These platform configurations are defined in applicable documents 2.2 and 2.3, respectively.

3.2.1.3 Design Life. The SKSS will be designed to provide a minimum service life of thirty (30) years.

3.2.1.4 Holding Strength. The SKSS will provide sufficient holding strength to react environmental forces induced by the Design Extreme Sea State having a return period of one hundred (100) years. This requirement defines the SKSS maximum holding strength. Platform excursion in this sea state will be bounded by the requirement to prevent cold water pipe grounding and disengagement of the Electrical Transmission System Cable. The SKSS is not required to totally react loads imposed by sea states in excess of the Design Extreme Sea State.

3.2.1.5 Watch Circle. Watch circle radius is the maximum allowable horizontal excursion of the platform from its equilibrium position in the mooring. Platform excursion in any direction will be limited to ten percent of water depth, or 400 ft, in all seas from calm up to and including the Design Operational Sea State having a return period of three (3) years. This watch circle limitation will be modified as appropriate to the particular Electrical Transmission System concept selected for each SKSS concept.

It is desirable to maintain connection between Electrical Transmission System and plant without damage to the riser cable in sea states more severe than the Design Operational Sea State. This requirement, in terms of allowable watch circle exceedance is 800 ft for 3 hours.

The platform will be constrained by the SKSS to the extent required to prevent grounding of the cold water pipe, in all sea states up to and including the Design Extreme Sea State a return period of one hundred (100) years.

3.2.1.6 Platform Orientation. The SKSS will have the capability to alter platform orientation (azimuth) to wind, wave and current, as required for electrical transmission and platform stationkeeping. The range of allowable azimuth variation is a working limit of plant yaw rotation of 90 deg..

3.2.1.7 Cost. The SKSS life cycle cost shall be minimized commensurate with an acceptable level of risk. Consideration of future costs of power in Puerto Rico and of OTEC Commercialization, lead to OTEC plant cost allocation for SKSS not to exceed $10 M.

3.2.2 Physical Characteristics

SKSS physical characteristics will be developed in the course of SKSS design based on the eight concepts described in Reference 2.1.

3.2.2.1 Arrangements. These characteristics will be compatible with the arrangements of the two platforms. In particular, the vertical load imposed on the spar by the SKSS will not exceed reserve buoyancy or static stability in the moored, operational mode.

SKSS arrangements will be compatible with the Electrical Transmission System requirements of support and clearance to prevent fouling between systems. Adequate clearance will be provided between the SKSS and the seawater intake and discharge pipes mounted on the platform to prevent fouling of lines and pipes.

3.2.2.2 Materials. SKSS materials will be chemically compatible to prevent galvanic and chemical corrosion of SKSS and the other OTEC ocean systems.

3.2.3 Reliability

The reliability of the SKSS will be determined to be as high as practicable consistent with the other requirements as stated in this specification.

3.2.4 Maintainability

3.2.4.1 Inspection. The SKSS will be compatible with in-situ inspection techniques appropriate to near shore, deep water mooring operation, including use of manned and/or unmanned deep submersible inspection equipment as well as permanently installed monitoring instrumentation.

3.2.4.2 Maintenance. A maintenance program, including schedules for periodic in-situ inspection, testing, lubrication, removal and replacement as required to provide continuous performance of the SKSS at specified reliability will be determined.

3.2.5 Availability

N.A.

3.2.6 System Effectiveness Model

N.A.

3.2.7 Environmental Conditions

3.2.7.1 Site. The SKSS will be designed to react the environmental conditions off the coast of Puerto Rico at Punta Tuna, 17°57'N - 65°52'W. This site is approximately three (3) miles offshore, with water depth of 4000 ft and bottom slope of 10 to 18 degrees. The mooring may be deployed within five (5) miles of this site in either direction parallel to the coast.

3.2.7.2 Bathymetry. Bottom soil conditions are silt, clay, sand, mud.

3.2.7.3 Current. Current profile is shown in Fig. 2-2.

3.2.7.4 Wind. Wind frequency of occurrence, direction and intensity are summarized in Table 2-1.

3.2.7.5 Sea States. Three groups of sea states are defined to determine SKSS loads.

3.2.7.5.1 Service Sea States. A set of discrete sea states will be defined, including intensity and cycles of occurrence, based on measured or derived frequency distributions for wind, wave and current. The SKSS will provide adequate fatigue strength for the cyclic loads encountered in these conditions.

3.2.7.5.2 Design Operational Sea State. The set of highest wind, wave and current conditions for which the SKSS will hold the platform within the required watch circle (3.2.1.5). The return period, or period of expected occurrence of this sea state is three (3) years. The wind, wave and current conditions for this sea state are summarized in Table 2-1.

3.2.7.5.3 Design Extreme Sea State. The set of highest wind, wave and current conditions for which station will be maintained by the SKSS. The return period of this Sea State is one hundred (100) years. The wind, wave and current conditions for this sea state are summarized in Table 2-1.

3.2.8 Transportability

The SKSS will be transportable to the extent required to deploy the moor at the site and to retrieve the moor at the completion of operation as required.

3.3 DESIGN AND CONSTRUCTION

Standards and specifications as defined in the Codes of Practice for offshore materials and construction, including the American Bureau of Shipping (ABS) Rules for Building and Classing Single-Point Moorings, and American Petroleum Institute standards and practice will be identified and applied in design of the SKSS.

3.4 DOCUMENTATION

N.A.

3.5 LOGISTICS

3.5.1 Maintenance

The maintenance capabilities must be provided to support the SKSS, both on-shore and on-board the OTEC platform, and including equipment to test, inspect, repair and replace SKSS components.

3.5.2 Supply

N.A.

3.5.3 Facility

N.A.

3.6 PERSONNEL AND TRAINING

TBD

3.7 FUNCTIONAL AREA CHARACTERISTICS

TBD

3.8 PRECEDENCE

N.A.

4. QUALITY ASSURANCE PROVISION

Testing to verify SKSS performance, design characteristics and operability will be determined. Test specification will include scope of effort and test objectives for SKSS components as well as complete operational SKSS.

Appendix C

CRITERIA AND ASSESSMENT PLAN FOR OTEC STATION KEEPING SUBSYSTEMS

IMODCO PROJECT 1103

19 APRIL 1979

Prepared by: Robert Scalese, OTEC Project Engineer
Reviewed by: John Vitale, OTEC Project Reviewer

Prepared for
Lockheed Missiles and Space Company, Inc.
Ocean Systems Division
Sunnyvale, California

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LIST OF ABBREVIATIONS

OTEC--Ocean Thermal Energy Conversion

SKSS--Stationkeeping Subsystems

SAL---Single Anchor Leg

TAL---Tension Anchor Leg

MAL---Multi Anchor Leg

TLM---Tension Leg Mooring

ASTM--American Society of Testing Materials

API---American Petroleum Institute

AISC--American Institute of Steel Construction

ABS---American Bureau of Shipping

AWS---American Welding Society

LRS---Lloyds Register of Shipping

SECTION II

DESIGN CRITERIA

II.1 Loading Analysis

The mooring system is subject to two basic types of loads; environmental loads and installation loads. Both of these categories are broken down into several loading definitions and are discussed in the following sections.

II.1.1 Environmental Loads

Environmental loads are those loads imposed on the SKSS by the environment (see Figure 1). Loads to be considered are:

1. Wave Load
2. Current Load
3. Wind Load
4. Earthquake Load

The loading conditions to be designed and checked for are:

1. Design Operational Sea State
2. Design Extreme Sea State

II.1.1.1 Wave Loading

Waves exert a dynamic load on ocean structures. For the OTEC/SKSS system with a moored vessel (SAL), the waves impart an energy on the vessel which must be absorbed by the mooring system. This energy is transferred to the mooring buoy via hawser or yoke, creating a mooring line tension. This tension is a major force in the system applied at the upper portion of the buoy. IMODCO's proprietary 'Tension

Leg Mooring' computer program (TLM) is used to analyze this force.

A horizontal wave force is exerted on the cylindrical cold water pipe. This force is related to the instantaneous components of water-particle velocity and acceleration which are in the direction of wave propagation. The wave force consists of two components, the drag force which is due to the horizontal particle velocity, and the inertial force which is related to the acceleration of the water particle. This force can be expressed by:

$$F = F_D + F_I = C_D \frac{w}{2g} D\, U|U| + C_M \frac{w}{g} \frac{\pi}{4} D^2 \frac{dU}{dt}$$

where:

F = wave force per unit length acting perpendicular to the member, lb/ft

F_D = drag force per unit length, lb/ft

F_I = inertia force per unit length, lb/ft

C_D = drag coefficient

w = weight density of water, lb/ft^3

g = gravitational acceleration, ft/sec^2

D = diameter of cylindrical member, ft

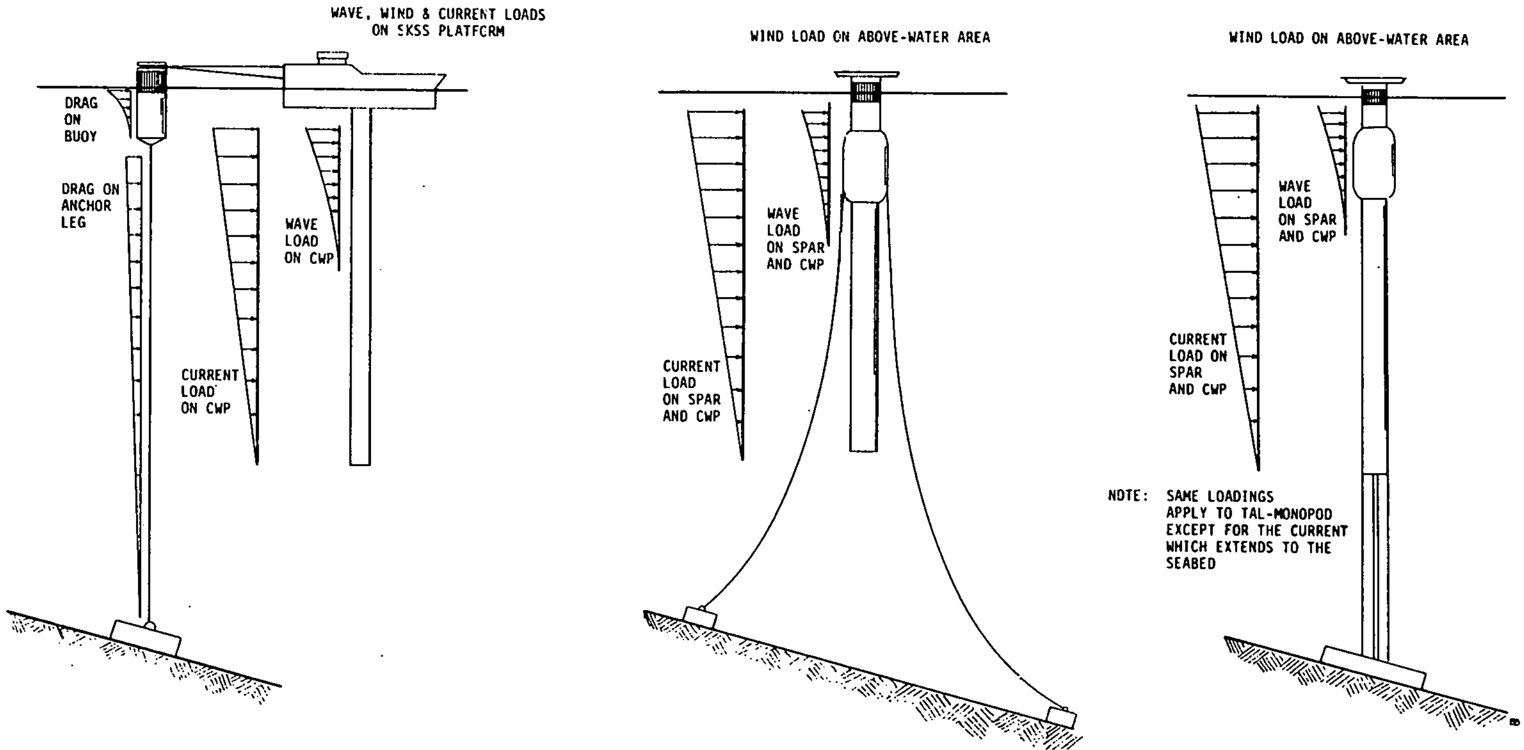
U = horizontal particle velocity of the water, ft/sec

$|U|$ = absolute value of U, ft/sec

C_M = mass coefficient

$\frac{dU}{dt}$ = horizontal acceleration of the water particle, ft/sec^2

Wave-induced vibrations of the various OTEC/SKSS are to be considered in the design, with the goal to avoid resonance between wave and structural frequencies. The criteria involved when checking frequencies is to be sure that the frequency



SAL-SINGLE POINT MOOR (SHIP ONLY)

MULTI-ANCHOR LEG (SPAR ONLY)

TENSION ANCHOR LEG (TAL) (SPAR ONLY)

ENVIRONMENTAL LOADINGS ON SKSS DESIGN CONCEPTS

IMODCO

FIGURE 1

of the SKSS does not fall in the range of the wave spectrum or vortex shedding.

The frequency of a floating OTEC/SKSS, such as the SAL and TAL, will be calculated with IMODCO's 'TOWER" program, which performs a dynamic simulation. The frequency of a fixed structure, the TAL-MONOPOD, will be checked with the following equation:

$$f_i = \frac{a_j}{2\pi} \left[\frac{EI}{(m + m_w)L^3} \right]^{1/2}$$

where:

E = Youngs Modulus
I = Moment of inertia of cross-sectional area
L = Length of TAL-MONOPOD
m = Mass of monopod
m_w = Added mass of water
a_j = Model coefficient = 3.52, 22.4, and 61.7 for the first three modes (re: Crede, 1965)

Vortices are shed in the wake of the circular pipe from the wave induced flow past the pipe. The vortex shedding occurs at a frequency f_V, which is a function of free-stream velocity, V_n, and the pipe diameter, D. This frequency is directly affected by the Strouhal number, S, a function of the Reynolds number.

$$f_V = \frac{S\ V_n}{D}$$

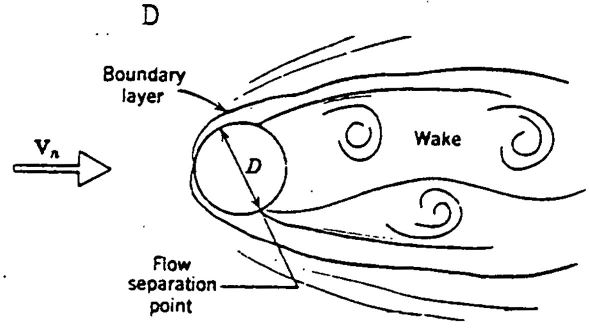


Figure 2 (re: McCormick, 1973)
Vortex shedding in wake of cold water pipe.

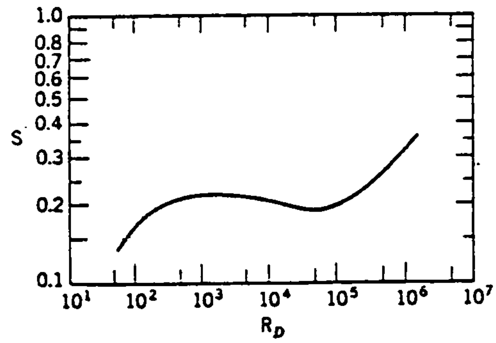


Figure 3 (re: McCormick, 1973)
Strouhal number for vortex shedding.

II.1.1.2 Current Loading

The current exerts a horizontal drag force on the vessel, spar, and coldwater pipe. The force is directly dependent on the projected cross-sectional area and the current velocity. The force must be calculated at incremental lengths along the pipe due to the variations in current velocity. This drag force may be expressed by the equation:

$$F_D = \frac{1}{2} \rho V_c |V_c| A$$

where:

F_D = Drag force

$\frac{w}{g} = \rho$ = Mass density of water

Vc = Current velocity

A = Project cross-sectional area

II.1.1.3 Wind Loading

The wind force is treated as a steady horizontal force acting on the projected above-water area of the platform and/or spar. IMODCO has an in-house computer program called 'SWING' to calculate the wind force. Inputs to the program are projected areas above the waterline and wind velocity.

The wind forces may also be calculated using the following equation:

$$F = .00256\ V^2 C_S A$$

where:

F = Wind force, lbs

V = Sustained wind velocity, MPH

C_S = Shape coefficient

A = Projected area of object

The shape coefficients are as follows:

Object	Cs
Beams	1.5
Side of buildings	1.5
Cylindrical sections	0.5
Overall projected area	1.0

II.1.1.4 Earthquake Loading

Earthquake loads can impart significant loads to piled, large mass gravity, and self-embedment anchors due to lateral and vertical accelerations. Holding power of conventional drag embedment anchors may be reduced by its motions in the surrounding soil. If the design requires this analysis, two earthquakes shall be considered. The first is a medium-level (operating) earthquake with a return period of every 200 years, the second a high-level (survival, without catastrohpic failure) earthquake with a return period in the thousands of years.

The OTEC/SKSS system will be designed for two levels of earthquake activity for which it may be subject to: Strength and Ductility Levels. The Strength Level requires the SKSS be adequately sized for strength and stiffness to maintain all nominal stresses within yield or buckling.

The Ductibility Level is to insure that the SKSS has sufficient energy absorption capacity to prevent its collapse during intense earthquake motions.

II.1.2 Installation

Moving the components of the SKSS from the fabrication site to the offshore location imposes forces upon the component parts of the structure. The movement of large, heavy components requires that dynamic as well as static loadings be analyzed.

II.1.2.1 Components of Installation Forces

The installation forces to be considered as recommended by the API RP2A are as follows:

1. Lifting forces
2. Loadout forces
3. Launching forces
4. Uprighting forces

Lifting forces that occur on the structure may include both vertical and horizontal components. Horizontal loads occur when lifting slings are other than vertical. The motion of lift must be considered in determining the horizontal forces. A minimum load factor of two (2) must be used in the design of lifting padeyes.

Loadout forces occuring during transportation shall be determined considering the height, length, and period of waves which may be encountered during tow. Horizontal and vertical loads are imposed on a structure from supports it may be resting on in a barge, thus requiring knowledge of dynamic characteristics of the barge.

Launching and uprighting forces are dependent on how the structure arrives at the offshore site, whether horizontal on the barge in the water, or in a vertical tow position. Forces in this stage of installation occur mainly from lifting and submergence pressures.

II.2 Design Standards

The standards used in the design of the OTEC/SKSS mooring system are:

· ABS	Rules for Building and Classing Single Point Moorings
· ABS	Rules for Building and Classing Steel Vessels
· API RP2A	Recommended Practice for Planning, Designing, and Constructing Fixed Offshore Platforms
· AISC	Steel Construction Manual
· AWS D1.1	AWS Structural Welding Code
· ASME	Section VIII, Boiler and Pressure Vessel Code
· AWS A2.0	Standard Welding Symbols
· ASTM	American Society for Testing and Materials--Specifications
· ANSI B31.4	Liquid Petroleum Transportation Piping Systems
· API Spec 2F	API Specification for Mooring Chain
· SSPC	Surface Preparation Specifications
· NEC	National Electrical Code

The application of these standards along with appropriate safety factors for individual components are discussed in the following sections. Variations from these standards are to be based on sound engineering principles and are subject to the review of the approval agencies.

II.2.1 Structural Design

The structural components will be designed to withstand the external water pressure during tow, installation and operation in all the design sea states. The structure will be capable of resisting the internal bending moments and tensions in the system. Buoyant structural components will be segmented into a series of watertight compartments by means of watertight decks and bulkheads. The compartments will be arranged so that with any one compartment flooded, the mooring system will remain afloat under the maximum environment. For stresses resulting from the combination of maximum wind, wave, current, gravity and mooring loading, the stresses are not to exceed the values listed below:

- 80% of yield strength for tensile stresses
- 80% of either the buckling or yield strength, 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

In the case of combined gravity and mooring loads which include live loads other than those resulting from wind and wave forces, the stresses are not to exceed:

- 60% of yield strength for tensile stresses
- 60% of either the local buckling or yield strength, whichever is less, for compressive stresses
- 57% of either the buckling or yield strength, whichever is less, for compressive stresses
- 40% of tensile yield strength for shear stresses

Compressive stresses caused by combined axial, bending and local loadings are proportioned to satisfy the following requirement from the AISC code.

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

where:

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 smaller

Structural analysis programs which may be utilized are EASE2 and GIFTS4. Consideration is given for each loading condition, including the following:

- Transmission of the operating hawser load from the hawser attachment point(s) to the anchor leg attachment point(s) or to the foundation.
- Application of the maximum anchor load to the anchor leg attachment point including application of appropriate wave and hydrostatic loads, in the case of a fixed structure.
- Application of the maximum wave, wind and current loads in the case of a fixed structure.

For compression members of sufficient length to buckle elastically, the following equation is used to calculate buckling stress:

$$F_e = \Pi^2 E/(Kl/r)^2$$

where:

$$Kl/r \geq \sqrt{2\pi^2 E/F_y}$$

F_e = elastic buckling stress

F_Y = yield stress

E = modulus of elasticity

l = column length

r = lease radiud of gyration

K = an effective length factor to be determined as per the latest AISC code

The critical buckling stress of a column is calculated with the following equation:

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

where:

F_c = compressive buckling stress

Two major considerations are associated with the computing of bending stress. The first is the prevention against local buckling, which is done by reducing the effective flange areas in appropriate sections or reducing the allowable stress. The second consideration is elastic deformations due to the effects of eccentric axial loading. These bending moments are superimposed on the bending moments computed for other types of loadings. The combination of average shell membrane stress and bending stress at design operating pressure is limited to 50% of the ultimate strength, or the minimum yield strength, whichever is less.

Where repetitions of stress are of a known cyclic nature, the allowable design stresses for fatigue loading as defined by the AISC specifications will be applied. For tubular members and connections, and where the fatigue loading consists of a spectrum of high and low stresses (e.g., due to waves), the fatigue provisions of AWS D1.1 will apply.

II.2.2 Mooring Lines

The mooring system between the vessel and the SPM will be designed so that the operating hawser load divided by the number of separated mooring lines, through different fair leads, maximum number of 2, is not greater than 40% of the rated breaking strength of the mooring line. For a single mooring line, the operating hawser load will not be greater than 60% of the rated breaking strength.

II.2.3 Mooring Bearings

Bearings which carry the operating hawser load are to be designed with a safety factor of 2 without destructive yielding of the bearing surfaces.

II.2.4 Anchor Leg(s) and Anchor

Each anchor leg will be designed with a safety factor of three against breaking. The type of anchorage used for the anchor leg(s) is dependent on the seabed conditions. The minimum design safety factor against the pullout of the anchor point is 2.

II.2.5 Pile and Pile Foundation

The design criteria used in the design of the piles and pile foundations are recommended in the API RP2A.

The piles, which anchor the mooring system, shall be designed to develop adequate capacity to resist the maximum axial bearing and pullout loads with an appropriate factor of safety. The allowable pile capacities are determined by dividing the ultimate soil capacities by the factor of safety of 2.

The ultimate bearing capacity (Q_d), needed for determining the allowable pile capacity, is calculated by the following equation:

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

where:

Q_t = skin friction resistance, lb

Q_p = total end bearing, lb

f = unit skin friction capacity, lb/ft^2

A_s = side surface area of pile, ft^2

q = unit end bearing capacity, lb/ft^2

A_p = gross end area of pile, ft^2

qA_p should not exceed the capacity of the internal plug

The pile foundation will be designed to sustain lateral loads, whether static or cyclic. A safety factor of 2 on the load to foundation is used under normal operating conditions and the maximum deflection of the pile will not be greater than 1/10 the pile diameter. The maximum steel stress associated with the factor of safety of 2 is not to exceed 0.66 F_y.

Ocean structures with foundations on the seabed experience an erosion process called scour, the removal of seafloor soils by currents and waves. Scour can result in removing vertical and lateral support for the foundation, causing overstressing of foundation elements and undesirable settlements. Scour prevention to eliminate the associated problems will be recognized in the design if needed.

II.3 Materials

Specifications for all materials used will conform to applicable standards as set forth by the governing classification requirements. All materials will have allowable stresses and load carrying capacities determined in accordance with a recognized standard.

Corrosion is considered when selecting materials. All materials have appropriate resistance to corrosion and are chosen to avoid electrolytic corrosion problems. Also, materials are adequately protected from the effects of corrosion and/or extra material is provided as corrosion allowance.

In selecting the material the question of weldability is considered. A suitable material is selected to ensure that cracking does not occur in the heat affected zone. Therefore, material thickness, carbon equivalent, welding process, consumables and preheat are considered when material selection is made.

Materials have an appropriate standard of notch toughness. Care is taken when adopting requirements for heavy steel sections and higher steel strengths.

II.3.1 Structural Steel

IMODCO normally utilizes structural steels for ships with a yield point of $\gtrsim$36 KSI. Variations of this are considered when the environmental temperature requires additional consideration of the V-notch toughness.

II.3.2 Cement Grout and Concrete

Cement grout, used in pile applications for load transfer, should be of a non-shrinking expansive type with a minimum compressive strength of 1500 psi in 24 hours.

The concrete mix used should be selected on the basis of shear strength, bond strength, and workability for underwater placement including cohesiveness and flowability. The water-cement ratio should be less than 9.45 with a sand content greater than 45%.

II.3.3 Mooring Chains

Extra high-strength U-3 grade chain and chain fittings are used in designs utilizing anchor legs. The diameter is selected such that under the maximum design load, a minimum factor of safety of three is maintained over the rated breaking strength. Oil rig quality and super-proof quality chains may be used if that strength level is necessary. Also, kevlar and wire rope may be substituted for chain.

II.3.4 Standard Material and Spec. Callout

ITEM	MATERIAL
Buoy Hull & Arm Assemblies	ASTM-A-36
	ASTM-A-131 GrA less than 3/4"
	ASTM-A-131 GrD 3/4" to 2"
Piles & Structural Pipe	ASTM-A-36
	ASTM-A-139 GrB
	ASTM-A-53 GrB
	API Spec 5L GrB

ITEM	MATERIAL
Chain	ABS Gr3 LRS Gr U-3
Rubbing Casting & Chain Stopper	ASTM-A-27 Gr70-40
Flanges-Forged	ASTM-A-105 Per ANSI B16.5
Flange Bolts	316. S.S.
Gaskets	Neoprene-Asbestos
Misc. Bolts & Nuts	ASTM-A-193-B7 ASTM-A-194-2H
Triangle Tow Plates	ASTM-A-572 Gr42
Highly Stressed Critical Members or Those Subjected to Repetitive Loads	Fine Grained Normalized Steels ASTM-A-131 GrD,E ASTM-A-131 Gr DH32,36 & EH32,36 HY-80, HY-100 ASTM-A-633 GrA,B,C,D,E

SECTION III

RELIABILITY AND PERFORMANCE ASSESSMENT

III.1 Mooring System Reliability

The mooring system design concepts for the OTEC/SKSS are systems which are designed to function satisfactorily for the 10 years design life. Three of the design concepts, the MAL for a SPAR, the TAL, and the TAL-MONOPOD, utilize no moving parts except for flexibility motions. This absence of moving parts greatly increases the reliability of a mooring system.

Random failure of a mooring component can be caused by factors such as corrosion, fatigue, abrasion and overloading due to dynamic instability. These factors can all be designed against with high-technology methods which greatly reduces the probability of failure.

Structural steel used in the design is tested and approved by the ASTM, thus assuring the quality and reliability of the material. The chain used in various applications is made in continuous lengths, with a specimen of four links removed for tests to assure the rated proof and breaking strengths.

There is no way to totally insure complete reliability for a mooring in deep ocean water, especially when susceptible to hurricane conditions. However, good engineering methods can greatly reduce the risk of failure. Figure 4 summarizes the uncertainties to be guarded against.

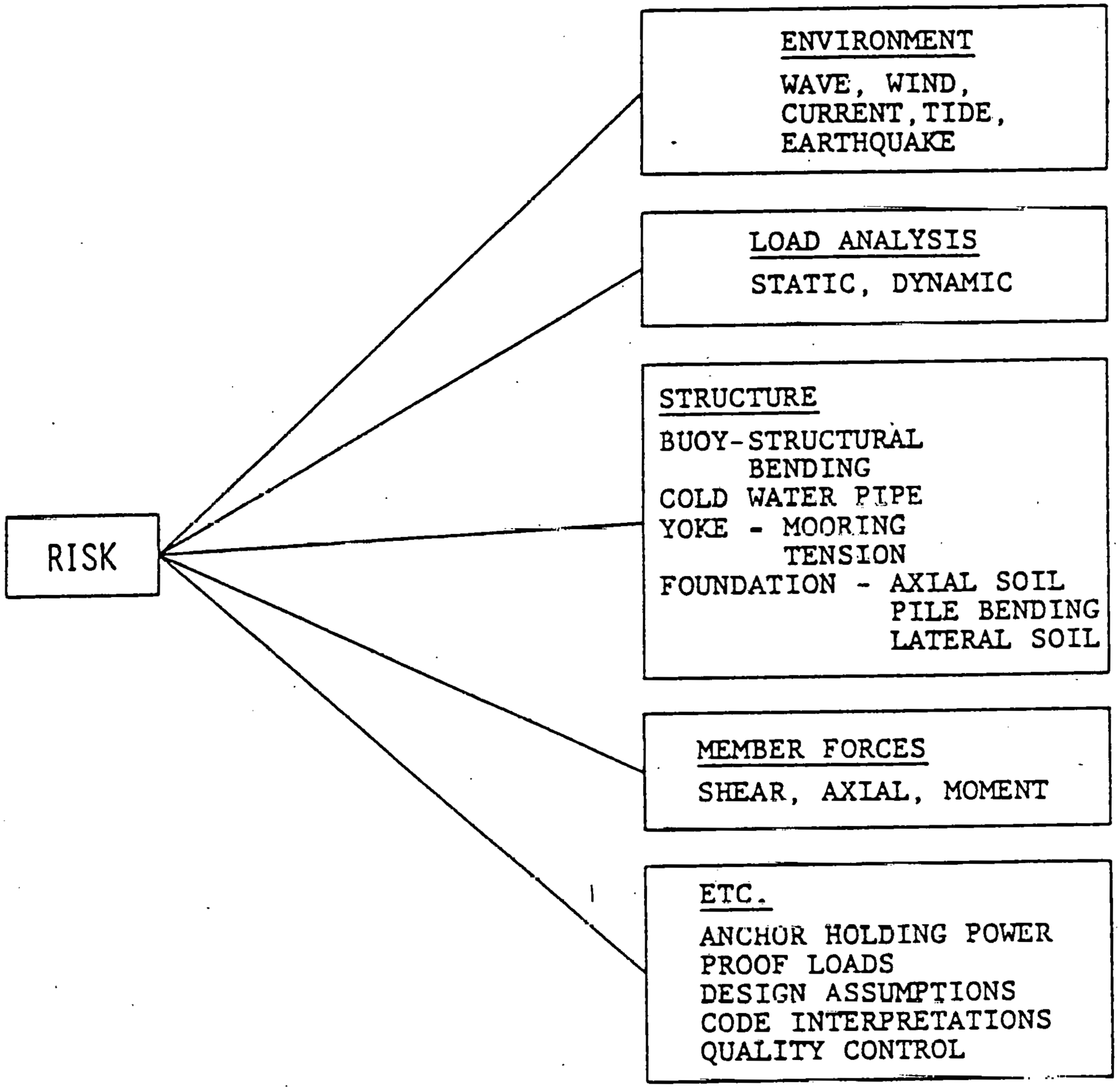


FIGURE 4 SKSS RISK MODEL - UNCERTAINTIES FOR RISK ANALYSIS

III.2 Terminal Component Life Spans

The following are typical replacement programs for offshore mooring terminals. Similar programs are adaptable for the OTEC/SKSS program, based on prior experience, and review and analysis of the final configuration.

A. All structural components are estimated to have at least an 18 year service life with proper maintenance.

B. Internal coating systems--5 to 7 years.

C. External coating systems--3 to 5 years.

D. Self-lubricating bearing at yoke and tri-axial universal joint--8 years.

E. Main bearing of tri-axial swivel--replace seals 8 to 10 years.

F. Anodes--replace after 3 years at splash zone; service life for rest of structure.

G. Ballast piping and sounding tubes--10 years.

H. Terminal fendering--4 to 5 years.

I. Navigation light fixture--7 to 10 years.

J. Access hatch seals and gaskets--3 to 5 years.

K. Hawser assembly--6 months to 1 year.

L. Chain--20 years.

III.3 Performance Assessment

A performance simulation of the OTEC/SKSS will be performed by computer analysis and other analytical methods. Performance characteristics that will be analyzed are watch circle excursion, tension in mooring components, SKSS stability, and component stresses.

III.3.1 Computer Programs

Most of the SKSS performance assessment will be performed by computer analysis. In the following sections are descriptions of the programs to be used and their application to the OTEC/SKSS project. TLM, TOWER, CEDP and CSCO are programs which are proprietary to IMODCO.

III.3.1.1 'TLM'

TLM is a static analysis program of a tension leg mooring. The program calculates the mooring force between ship and buoy, buoy and/or riser inclination angle, riser axial tension, base forces, and displacement from static rest position (watch circle). TLM will be used in the analysis of the SAL-SINGLE POINT MOOR and TAL mooring system.

III.3.1.2 'TOWER'

TOWER performs a dynamic simulation of a tension leg mooring. It provides the motions of tension leg throughout the wave period along with bending moments. The program also computes the natural period of the system so that resonance may be checked. TOWER will also be used for the SAL and TAL systems.

III.3.1.3 'CEDP'

The CEDP computer program will be used in the analysis of the MAL system. CEDP is a static deflection program which calculates forces based on deflections and energy absorption. Chain tensions, suspended chain lengths, hawser/yoke tension, anchor loads, and spar displacements are calculated.

III.3.1.4 'CSCO'

CSCO performs the dynamic simulation for the MAL. The buoy excursion is analyzed in a time history along with the anchor leg forces. Various wave heights and periods may be input to check excursions in the storm condition.

III.3.1.4 'MARRS'

MARRS, computer program for marine riser response systems, will be used for a dynamic simulation of the SAL-SINGLE POINT MOOR, the TAL and TAL-MONOPOD mooring systems for the SKSS. The program will calculate the natural frequency of the systems, along with a time history analysis of displacement and stress.

III.3.1.6 'EASE2' and 'GIFTS4'

EASE2 and GIFTS4 are the programs which may be utilized if the finite element analysis of the SKSS is required. Both programs are capable of a complete stress analysis including problems of temperature gradients. Finite element analysis will be used only on the design concept chosen for the preliminary design task.

III.4 Inspection

To insure continuous service of the OTEC/SKSS, inspection and testing must be performed during the fabrication, erection and operational phases. Inspection and tests are necessary in assuring defects do not turn into catastrophic failure.

III.4.1 Fabrication and Erection Inspections

All fit-ups (joint preparation prior to welding) and completed welds will be subject to visual inspection. Materials and fabricated items specified for non-destructive testing will be tested to acceptance criteria and the results will be recorded.

Weld profiles in tubular joints shall merge smoothly with the base metal of both brace and chord, with undercut not exceeding .01 inch. Welds subjected to non-destructive testing by radiography or other methods shall meet the requirements of AWS D1.1.

All buoyancy tasks shall be pressure tested when applicable. During pressure tests, the following stress limitations will apply:

1. In hydrostatic testings, the average shell membrane stress is limited to 90% of the minimum specified yield strength.
2. Under pneumatic testing, shell membrane stress is limited to 80% of yield strength.
3. The combination of average shell membrane stress and bending stress at design operating pressure is limited to 50% of the ultimate strength, or the minimum specified yield strength, whichever is less.

III.4.2 Service Inspection

Periodic surveys during the life of the structure will be conducted to detect evidence of damage, check effectiveness of cathodic protection, and plan repairs.

The splash zone region is most subject to damage and will be inspected yearly. High corrosiveness and floating debris may cause faster deterioration than in other regions and should be checked by visual inspection. Supplementary means of inspection, such as ultrasonic and radiographic, shall be used when possible.

The following maintenance schedule is suggested for use on SALMs, but may be applied to the SKSS. Local environment and terminal usage will dictate the actual requirements.

III.4.2.1 Daily Inspection

1. Check operation of navigation lights.
2. Check security of terminal to ensure all hatches are firmly closed.

III.4.2.2 Weekly Inspection

1. Inspect mooring swivel bearing for free rotation.
2. Inspect bearings at barge end of yoke arms.
3. Inspect all manhole bolts for tightness.
4. Remove the blind flanges from the sounding pipes on the upper deck and sound all watertight pipes.

III.4.2.3 Monthly Inspection

1. Inspect all batteries for proper voltage.

2. Lubricate mooring swivel bearing.
3. Check all upper deck manhole gaskets for proper seal.

III.4.2.4 Yearly Inspection

1. Inspect all upper buoy works for any signs of structural weakness or damage.
2. Inspect anodes on buoy for deterioration, scrape clean and replace if necessary.
3. Check all mooring chains for orientation, wear and corrosion.
4. Check mooring chain tension.

SECTION IV

OPTIMIZATION METHODOLOGY

IV.1 Optimization of Single Point Moorings

The Single Point Mooring designed and installed today is a result of twenty years of continual change and improvement. Costs of materials, fabrication, transportation and installation has motivated an effort towards the optimization of SPMs. These efforts, along with their progress and results, are discussed in the following sections.

IV.1.1 Mooring Force Analysis

For each SPM design project, a parametric study of mooring forces is performed. The goal of the study is to find a mooring configuration that affords the lowest loads while still having acceptable operational characteristics. A sample of these characteristics is buoy excursion, buoy draft, and buoy dynamic response. It is recognized that lower forces result in smaller anchoring requirements. All holding power equipment, chain, anchors, piles and gravity/ballast, are paid for by the pound. Thus, a mooring force optimization cycle results in a lower cost.

IV.1.2 Weight Optimization

The weight optimization process is a subset of the design process. During the design stage, the smallest possible size for a buoy is sought after. The smallest buoy naturally results in a lighter buoy with a lower cost. Structural analysis has several optimization rituals including a computer program for framing weight optimization.

IV.1.3 Strength/Cost Analysis

Designing beam element strengths to the limit of allowable stresses is a process used in the reduction of cost. IMODCO has a proprietary program called 'SRATIO' which calculates the ratio of actual stress to allowable stress according to the API and AISC specifications. Obtaining this stress ratio will allow the designer to reduce (or increase) the beam element size so that the ratio approaches 1, which means the optimum beam size according to stress limitation.

IV.1.4 Model Test - Analysis Loop

For new development and special projects in severe environments, a model test and design analysis loop is established to study new techniques of handling forces, accurately establish loads, and assure system reliability.

The first step in the loop is to prepare a preliminary design based on experience and computer analysis. Expected loads are approximated for comparison to those received during model tests. The next step is to model test the preliminary design. Loads are recorded at this time to be used during the next structural analysis. During model tests the system is modified to find the optimum placement of anchoring devices or mooring gear. Also, alternate systems are tested for comparison to the primary design. Upon review of the model test results, a final design is prepared making use of the weight and strength optimization procedures. The final design is model tested to assure the system's performance is within the established design criteria.

IV.1.5 Feedback from Field

Feedback from the field pertaining to installation and operational experiences and difficulties has aided in the optimization of SPMs. The arrangement of the mooring arms and protection systems (cathodic protection, impact protection) have been greatly modified since the first SPM. Difficulties in installation can greatly increase costs, therefore the procedure of installations is changed when easier ways can be found.

IV.1.6 Optimization Limitations

Although the SPMs are designed to be as light and cost-effective as possible, there are restrictions that limit the optimization cycle. The ocean is a hostile environment and prediction of motions and forces resulting in it is most difficult. Due to this degree of difficulty in accurate predictions, stringent rules with high safety factors are followed. The rules and safety factors make it hard to design a truly lightweight, optimum cost ocean going system.

IV.2 System Effectiveness

Selection of a mooring concept for the SKSS should include considerations of the system's effectiveness. Effectiveness parameters which are associated with the project's objective are compatibility, capability and level of risk.

IV.2.1 Compatibility

One effectiveness parameter to consider is the compatibility of the design concepts to the mooring of the SKSS spar and cold water pipe. Compatibility factors to consider include:

1. Receiving loads transmitted from spar/cold water pipe.
2. Interference of mooring system to cold water pipe.
3. Effectively performing all the established performance criteria.

IV.2.2 Level of Risk

A level of risk is established by the environment's probability of exceedence of the survival storm. If a system is designed to survive the specified storm without adequate strength for a storm that exceeds that value, the system is considered to have a high level of risk. If a system has some residual strength or redundancy, it is considered to have a lower level of risk.

IV.2.3 Capability

A third parameter of effectiveness is the system's capability of performing the seakeeping task. Capability may be defined as follows:

> Capability is a measure of the system's ability to achieve the mission's objectives, given the system condition during the mission. Capability specifically accounts for the performance spectrum of the system.

Capability is not totally established by the system's hardware. Another factor is the mission assigned to the system. The large size of the spar, cold water pipe, and severe environments assigned to the mooring may lower the capability of some of the design concepts. Other factors to be considered may include the capability of repairing the system. Present technology lends itself to be more capable of repairs near the surface rather than at 4000 feet.

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6. Handbook of Ocean and Underwater Engineering, Myers, Holm, and McAllister, New York, 1969

Appendix D

DEEP OCEAN SHIP MOORING DATA AND RISK ASSESSMENT TABLES

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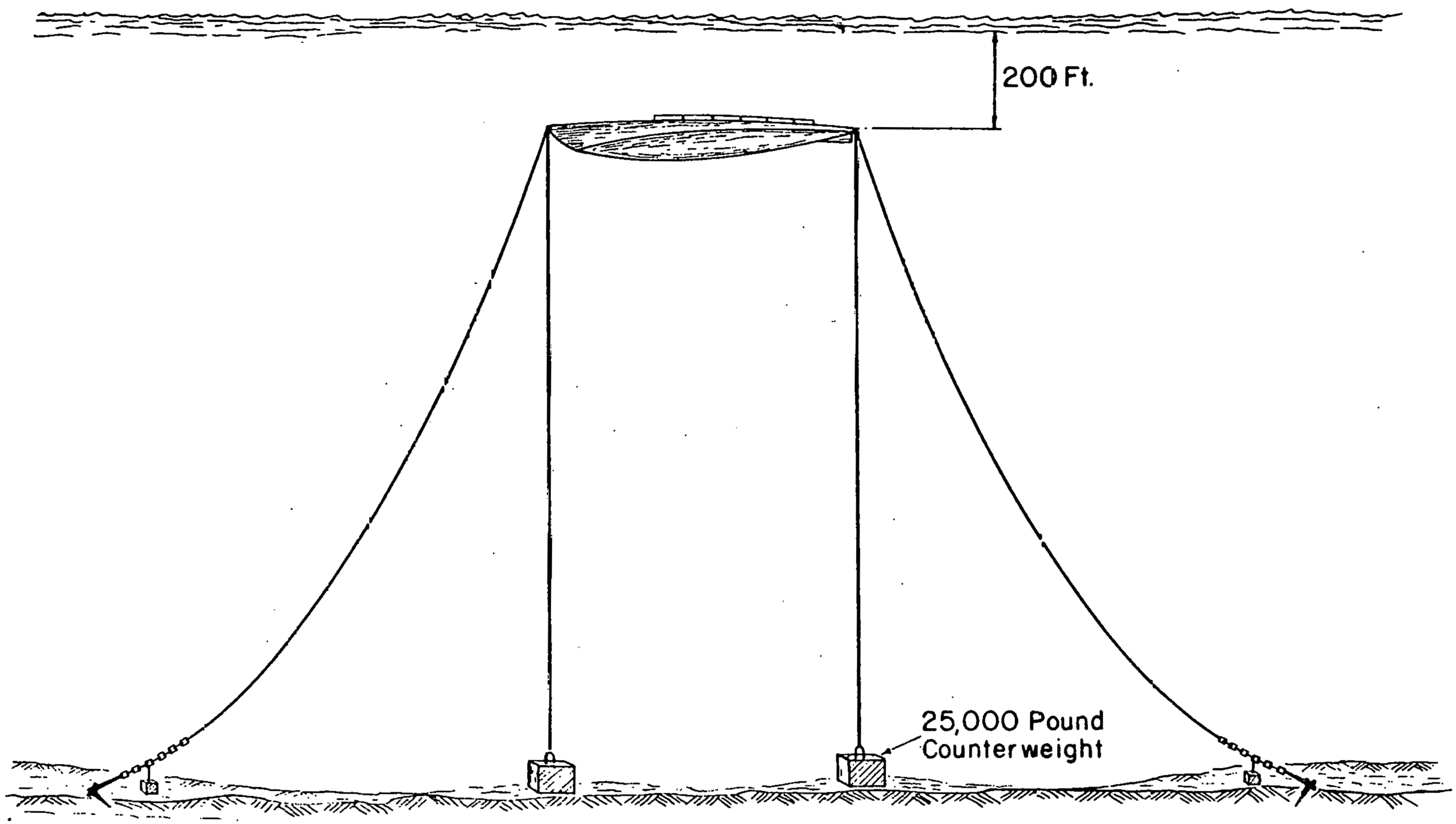
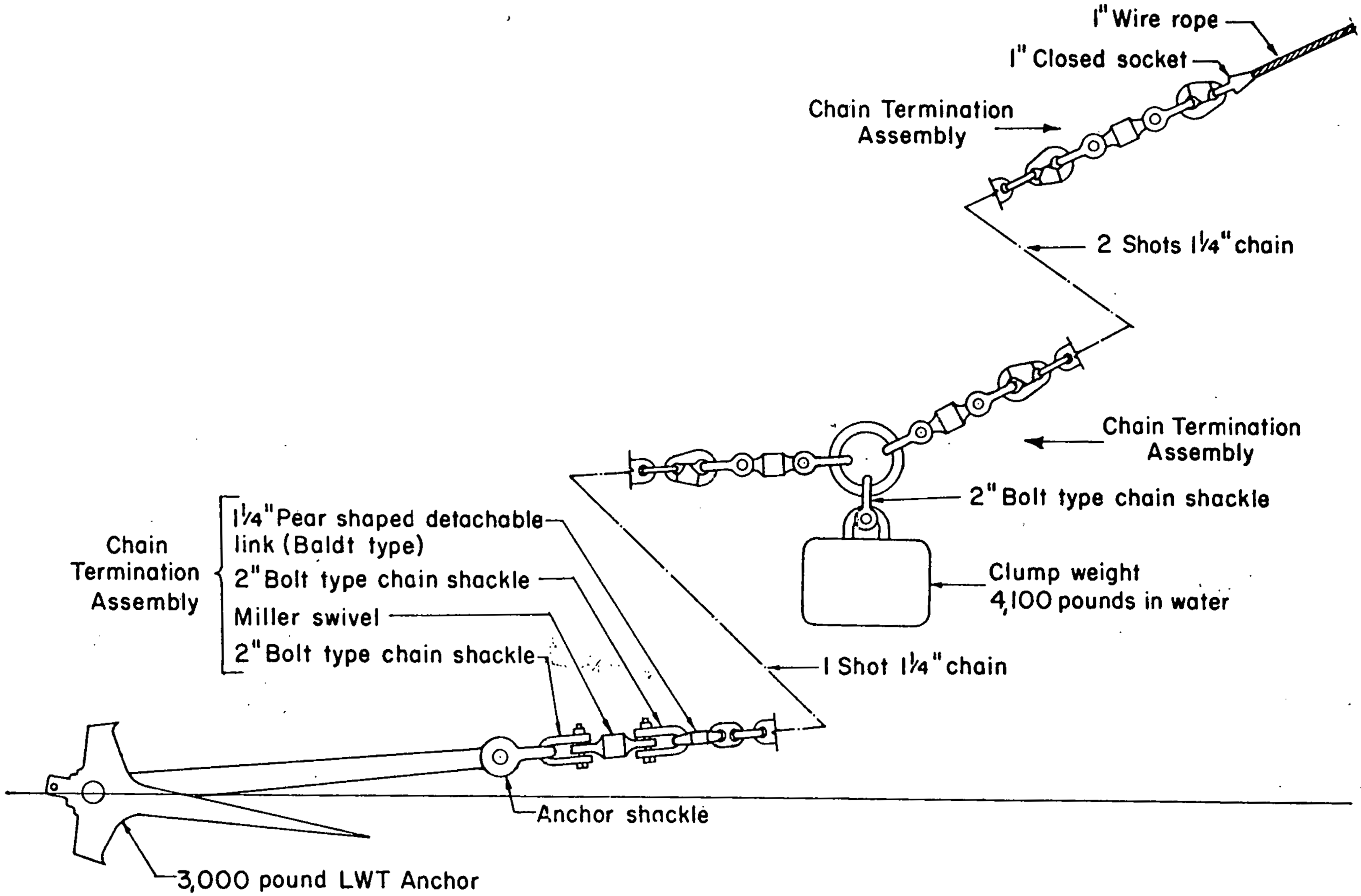
DEEP OCEAN SHIP MOORINGS (GREATER THAN 2000 FEET)

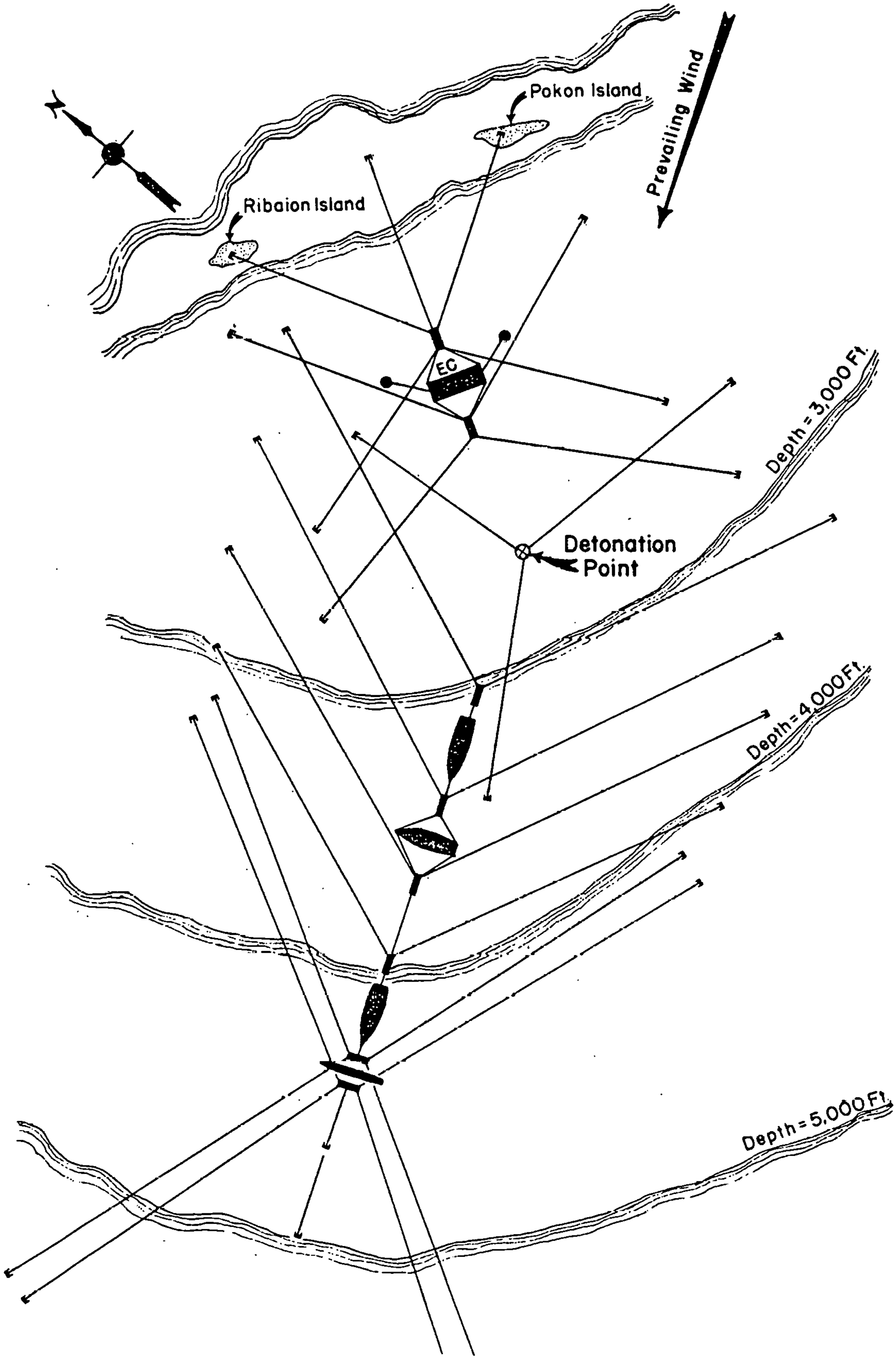
MOOR	INSTALL DATE	LOCATION OFF	WATER HULL DEPTH	MOOR TYPE	LEG DESIGN See Figure	FAIL DATE	FAILURE MODE APPARENT
SQUAW I Sub	1959	San Diego	6000' 200'	MAL-MPM 4 Legs	$1\frac{1}{4}$" Wire $1\frac{1}{4}$" Chain	1964	Hull Padeye
II	1965	"	3600' 200'	"	$1\frac{1}{4}$" Wire $1\frac{1}{2}$" Chain	1970	Lines and/or Fittings
III	1970	"	3500' 300'	"	"	1976	"
IV	1978	"	6200' 300'	"	$1\frac{1}{4}$"Torque Bal. Wire 2" Chain	1978	Installation incomplete; Leg entangled, later failed in storm.
HARDTACK Ship	1958	Eniwetok	5000'	MAL-MPM	1" Wire $1\frac{1}{4}$" Chain	None	
TOTO I	1959	Tongue of Ocean	5500'	MAL-MPM 3 Legs	1" Wire $1\frac{1}{4}$" Chain	1960	Buoy impacted and drawn to collapse depth by ships.
II	1962	"	"	MAL-MPM Complex	$1\frac{1}{4}$" Wire $2\frac{1}{2}$" Chain		Low utilization; Unconfirmed report of several failures.
DISCOVERER 534 Drillship	1978	Thailand	3500'	MAL-MPM Turret 8 Legs	3" Wire $2\frac{1}{2}$" Chain		None for 90 days; Wind 30 kt; Current 3-4 kt; Sea 12' max. Preten 70 Kips; Watch 2% max.
OCEAN RANGER Semi-Sub			3000' Claim	MAL-MPM 12 Legs	3" Wire $3\frac{1}{4}$" Chain		Untested near OTEC conditions



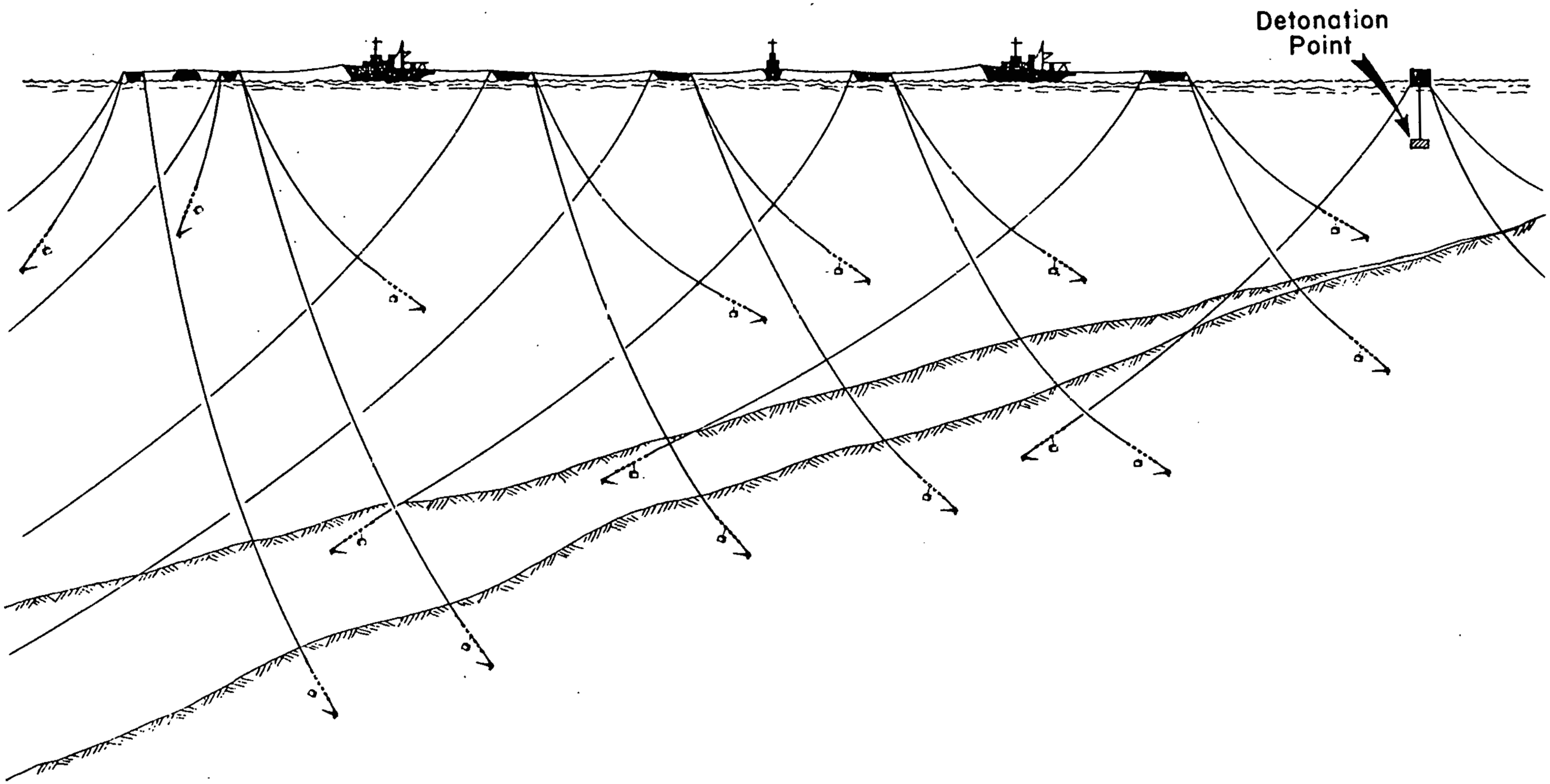
Final Configuration of the SQUAW Mooring



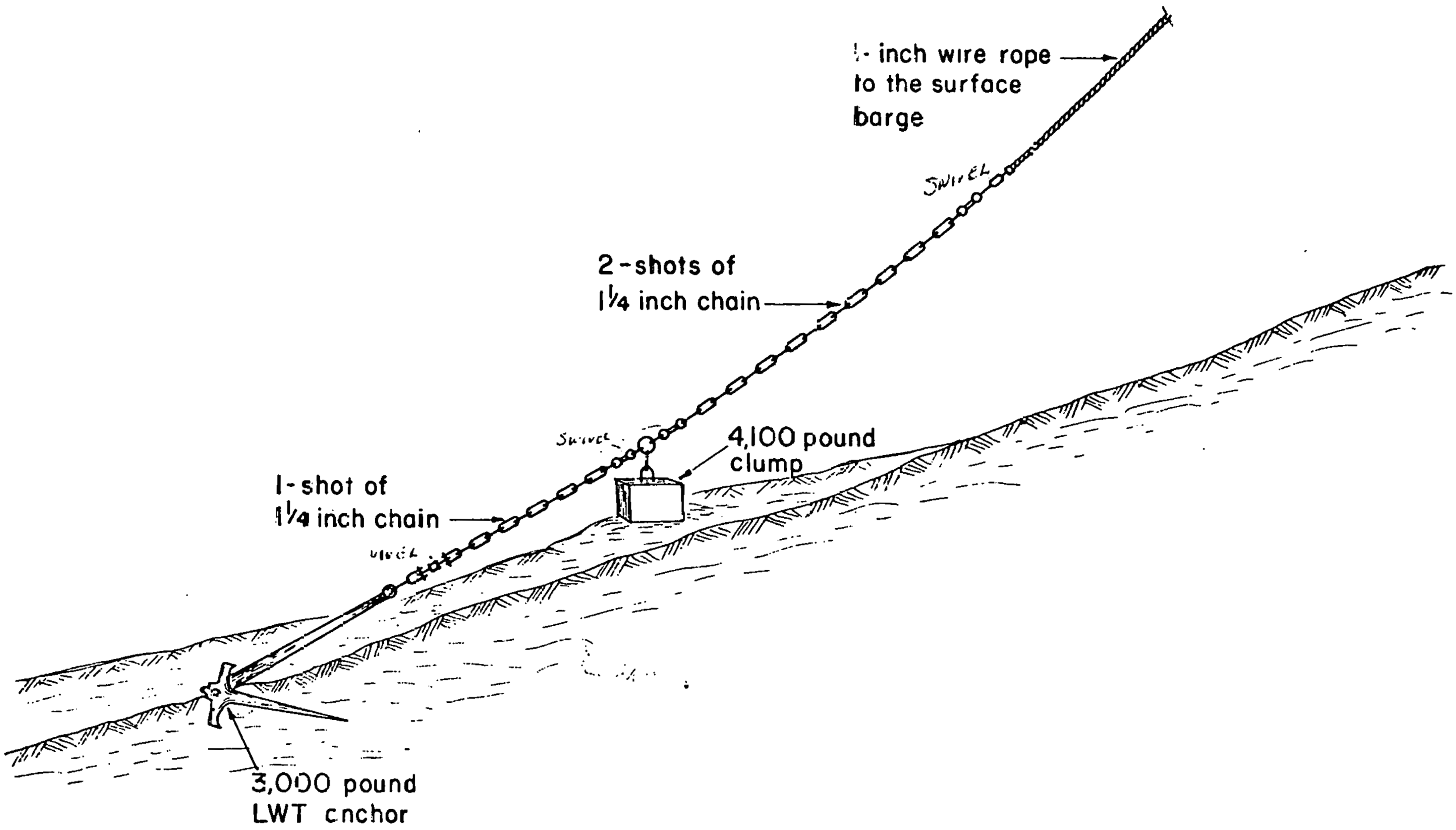
Details of the SQUAW Mooring Leg



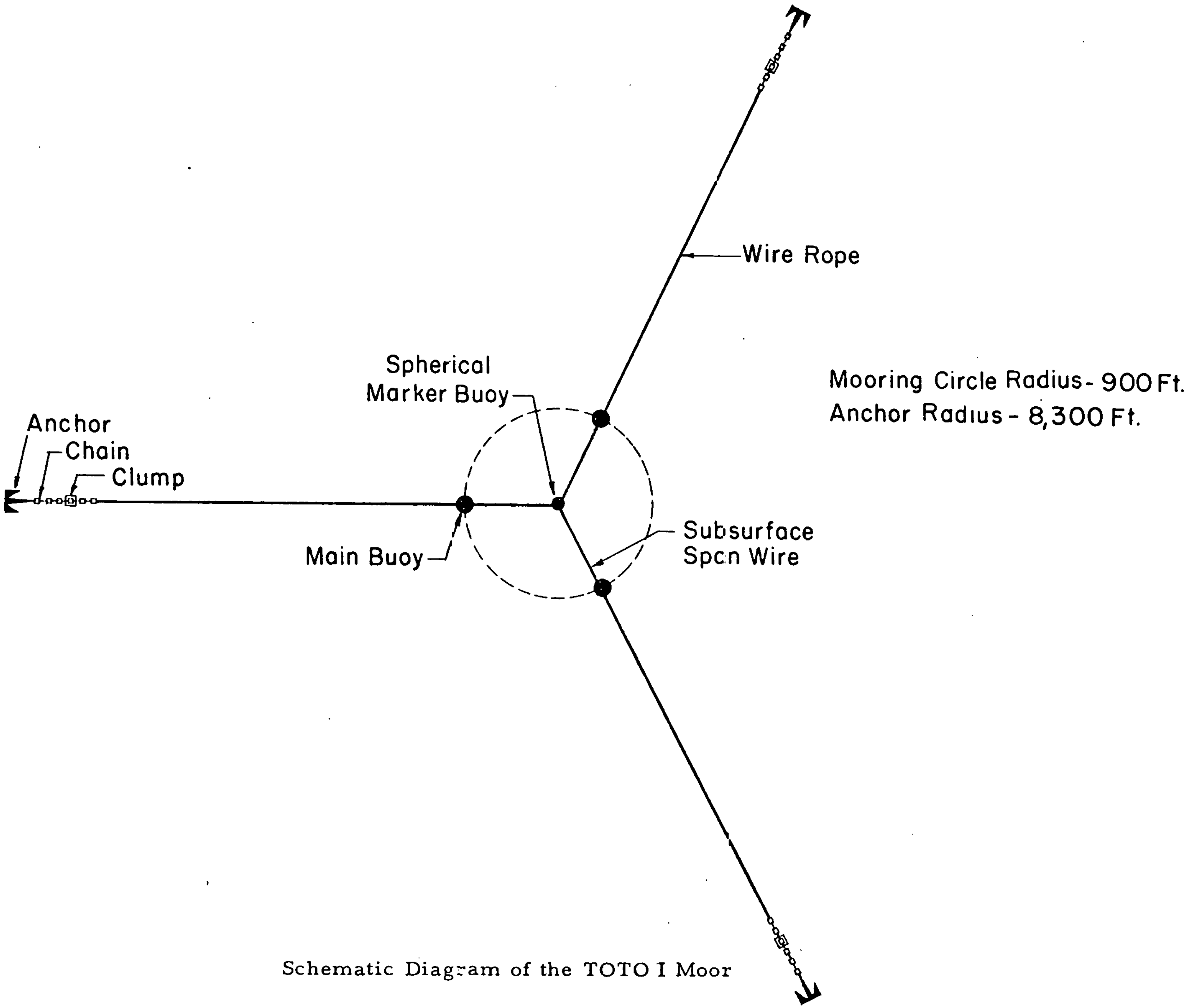
Mooring of Test Vessels for Operation HARDTACK



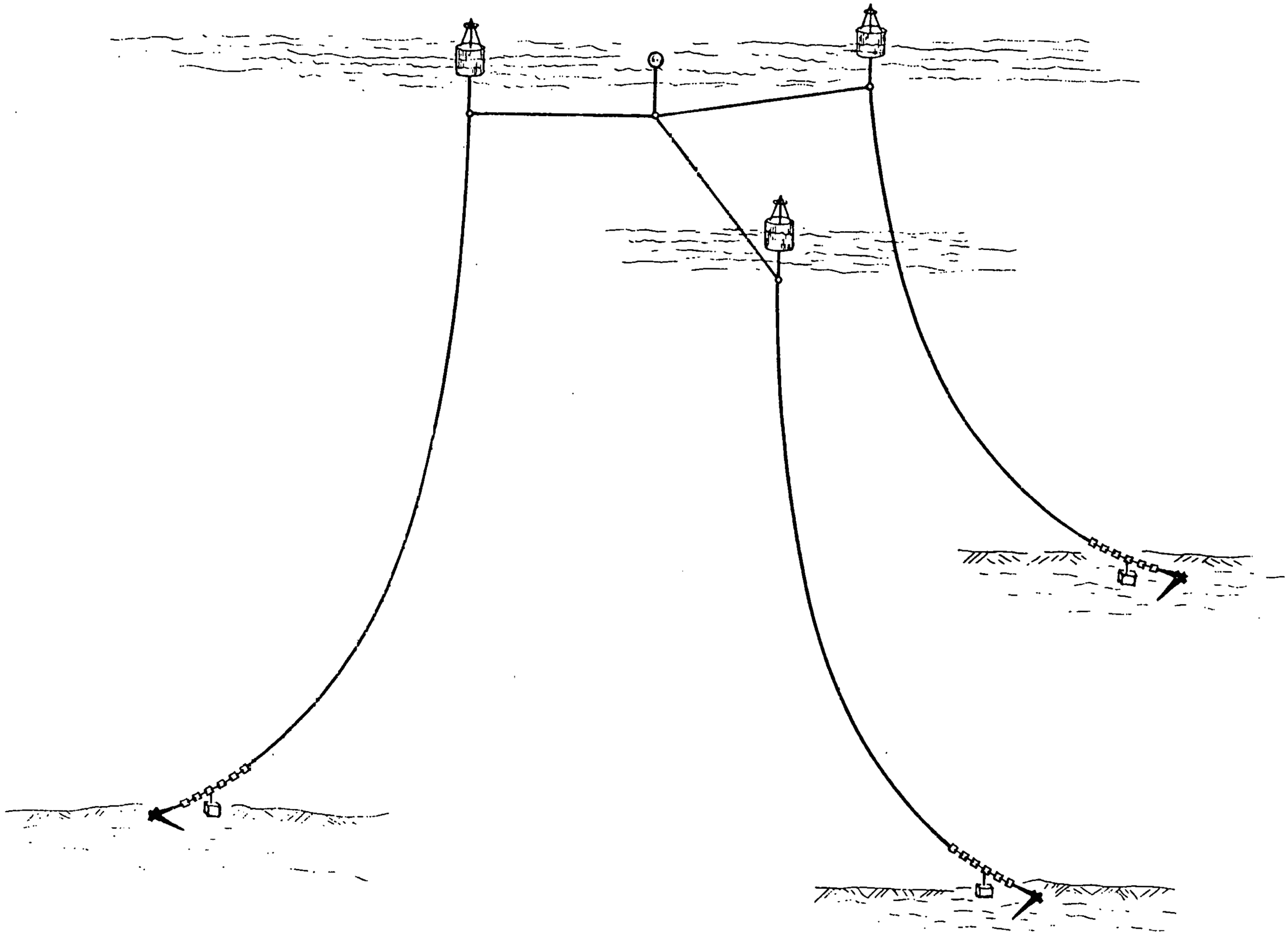
Complex Anchor Deployment Required for Deep Water Portion of Test Array



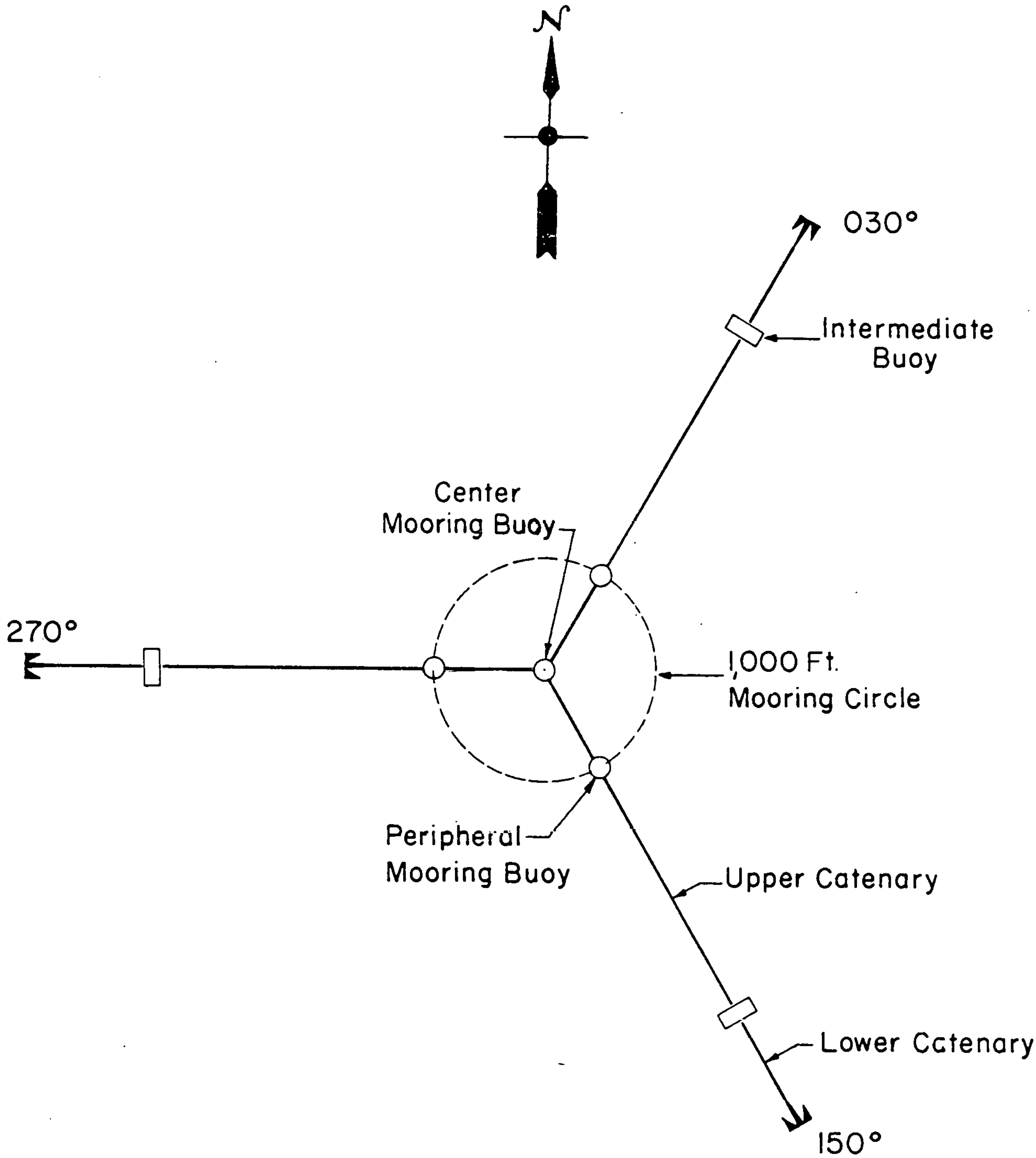
Typical Configuration of the Mooring Legs Used
for Operation HARDTACK



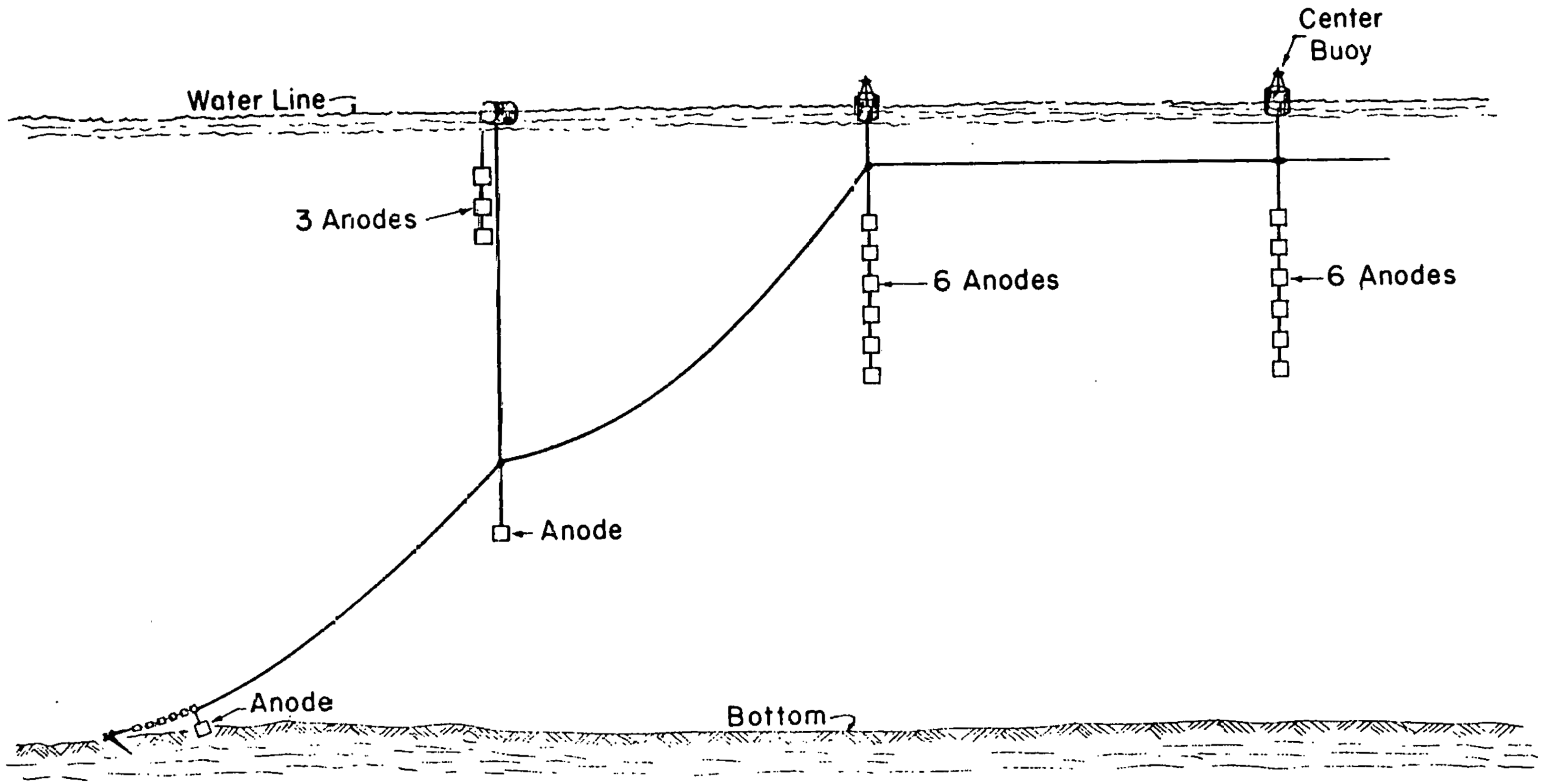
Schematic Diagram of the TOTO I Moor



Configuration of the TOTO I Moor as Installed



Schematic Diagram of the TOTO II Moor



Cathodic Protection System for the TOTO II Moor

MAL-MPM-ACTIVE TENSIONING (SPAR)
CHANGES FROM TAL (SPAR)

RISK AND CRITICALITY ASSESSMENT MATRIX

FAILURE MODES	ETC DAM FLOOR	ETC DAM PIPE	ETC DAM LEG	SLIP RING FAULT	ANCH PULL OUT	LEG DAM MULTI	LEG DAM PIPE	MOOR CONN DAM	BUOY DAM MULTI	SHIP CONN DAM
RISK CONDITIONS										
Pretension										
Dyn Tension										
Motion										
Unproven Com										
Multi-Interf										
Com Interact										
Com Environ										
Com Install										
RISK FACTORS										
RISK REDUCT OPPORTUNITY										
Env Measure										
Rep Analysis										
Load Mitigate		+						+	+	
Self Load "								--	--	
Redundancy										
Safety Factor										
Rep Testing										
Det-Correct										
Install Simpl										
RISK REDUCT FACTOR		10						6	7	
NET RISK FACTOR		0						4	3	
CRITICALITY DETERMINANTS										
Pers Injury										
Downtime										
Recover Cost										
CRITICALITY FACTOR		2							10	
RISK CRITICALITY FACTOR		0						40	30	

MAL-MPM (SPAR)
CHANGES FROM TAL (SPAR)

RISK AND CRITICALITY ASSESSMENT MATRIX

FAILURE MODES	ETC DAM FLOOR	ETC DAM PIPE	ETC DAM LEG	SLIP RING FAULT	ANCH PULL OUT	LEG DAM MULTI	LEG DAM PIPE	MOOR CONN DAM	BUOY DAM MULTI	SHIP CONN DAM
RISK CONDITIONS										
Pretension										
Dyn Tension										
Motion										
Unproven Com										
Multi-Interf										
Com Interact										
Com Environ										
Com Install										
RISK FACTORS										
RISK REDUCT OPPORTUNITY										
Env Measure										
Rep Analysis										
Load Mitigate										
Self Load "							+		−	
Redundancy					+	+				
Safety Factor										
Rep Testing										
Det-Correct										
Install Simpl										
RISK REDUCT FACTOR										
NET RISK FACTOR										
CRITICALITY DETERMINANTS										
Pers Injury										
Downtime										
Recover Cost										
CRITICALITY FACTOR										
RISK CRITICALITY FACTOR					10	10	0		30	

TAL MONOPOD
CHANGES FROM TAL

RISK AND CRITICALITY ASSESSMENT MATRIX

FAILURE MODES	ETC DAM FLOOR	ETC DAM PIPE	ETC DAM LEG	SLIP RING FAULT	ANCH PULL OUT	LEG DAM MULTI	LEG DAM PIPE	MOOR CONN DAM	BUOY DAM MULTI	SHIP CONN DAM
RISK CONDITIONS										
Pretension										
Dyn Tension										
Motion										
Unproven Com										
Multi-Interf										
Com Interact										
Com Environ										
Com Install										
RISK FACTORS										
RISK REDUCT OPPORTUNITY										
Env Measure										
Rep Analysis										
Load Mitigate										
Self Load "	+					−	+	++		
Redundancy										
Safety Factor										
Rep Testing										
Det-Correct										
Install Simpl										
RISK REDUCT FACTOR	10					4	10	9		
NET RISK FACTOR	0					6	0	1		
CRITICALITY DETERMINANTS										
Pers Injury										
Downtime										
Recover Cost										
CRITICALITY FACTOR	2					10	10	10		
RISK CRITICALITY FACTOR	0					60	0	10		

MAL-MPM (ACTIVE TENSIONING)
CHANGES FROM MAL-MPM

RISK AND CRITICALITY ASSESSMENT MATRIX

FAILURE MODES	ETC DAM FLOOR	ETC DAM PIPE	ETC DAM LEG	SLIP RING FAULT	ANCH PULL OUT	LEG DAM MULTI	LEG DAM PIPE	MOOR CONN DAM	BUOY DAM MULTI	SHIP CONN DAM
RISK CONDITIONS										
Pretension										
Dyn Tension										
Motion										
Unproven Com										
Multi-Interf										
Com Interact										
Com Environ										
Com Install										
RISK FACTORS										
RISK REDUCT OPPORTUNITY										
Env Measure										
Rep Analysis										
Load Mitigate	+					−				−
Self Load "										
Redundancy										
Safety Factor										
Rep Testing										
Det-Correct										
Install Simpl										
RISK REDUCT FACTOR	8					7				8
NET RISK FACTOR	2					3				2
CRITICALITY DETERMINANTS										
Pers Injury										
Downtime										
Recover Cost										
CRITICALITY FACTOR	2					10				10
RISK CRITICALITY FACTOR	4					30				20

MAL-MPM (TURRET OR ROTARY)
CHANGES FROM MAL-MPM

RISK AND CRITICALITY ASSESSMENT MATRIX

FAILURE MODES	ETC DAM FLOOR	ETC DAM PIPE	ETC DAM LEG	SLIP RING FAULT	ANCH PULL OUT	LEG DAM MULTI	LEG DAM PIPE	MOOR CONN DAM	BUOY DAM MULTI	SHIP CONN DAM
RISK CONDITIONS										
Pretension										
Dyn Tension										
Motion										
Unproven Com										
Multi-Interf										
Com Interact										
Com Environ										
Com Install										
RISK FACTORS										
RISK REDUCT OPPORTUNITY										
Env Measure										
Rep Analysis										
Load Mitigate	++					++		++		
Self Load "										
Redundancy										
Safety Factor										
Rep Testing										
Det-Correct										
Install Simpl										
RISK REDUCT FACTOR	9					9		8		
NET RISK FACTOR	1					1		2		
CRITICALITY DETERMINANTS										
Pers Injury										
Downtime										
Recover Cost										
CRITICALITY FACTOR	2					10		10		
RISK CRITICALITY FACTOR	2					10		20		

MAL-SPM
CHANGES FROM SAL-SPM

RISK AND CRITICALITY ASSESSMENT MATRIX

FAILURE MODES	ETC DAM FLOOR	ETC DAM PIPE	ETC DAM LEG	SLIP RING FAULT	ANCH PULL OUT	LEG DAM MULTI	LEG DAM PIPE	MOOR CONN DAM	BUOY DAM MULTI	SHIP CONN DAM
RISK CONDITIONS										
Pretension						−		−		
Dyn Tension						−		−		
Motion								+		
Unproven Com						−		−		
Multi-Interf										
Com Interact			+			+		+		
Com Environ										
Com Install			+			+		+		
RISK FACTORS			10			10		10		
RISK REDUCT OPPORTUNITY										
Env Measure										
Rep Analysis						−		−		
Load Mitigate										
Self Load "						−		−		
Redundancy						+		+		
Safety Factor						+		+		
Rep Testing								−		
Det-Correct						+				
Install Simpl								−		
RISK REDUCT FACTOR			7			7		5		
NET RISK FACTOR			3			3		5		
CRITICALITY DETERMINANTS										
Pers Injury										
Downtime										
Recover Cost										
CRITICALITY FACTOR										
RISK CRITICALITY FACTOR			6			30		50		

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